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Critical Parts Retrieval and Profit Maximization for Medical Sustainability using Design for Disassembly and Modularity

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This thesis is dedicated to my wonderful mother Smt. Lalitha Kumari

………With respect and love

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by

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Abstract

With rising medical expenditure and increase in medical waste, it is highly imperative to look for ways to recycle and reuse medical products. Even though the reprocessing industry has made use of optimum disassembly techniques in order to derive the maximum possible profit from each medical device, it is limited since most of the medical devices can be hard to recycle without a change in the basic design complying with life cycle goals. This study will introduce a framework which will help to combine the optimum disassembly techniques with the modularity concept in order to come up with recommendations for redesigning a medical product in order to extract maximum profit from a medical device not possible from the initial design while at the same time fulfill sustainability goals by extracting maximum useful material easily for material extraction and recycling purposes

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Chapter 1: Introduction

1.1 General

The Medical industry is well known for products that are used once and then thrown away because they become biohazards when used in patients. Most of the medical devices are mostly a “1 use” item; and this is where the objectives of medical parts and sustainability contradict themselves. Sustainability is focused on recycle, reduce and reuse. Manufacturing Medical Parts that are focused on reducing parts is possible, recycling becomes very difficult and reusing is almost impossible. That is why trying to combine these two growing areas become a great challenge. Sustainability is about helping the environment; medical is about helping human health. Even though both aspects might look like they are closely related and easy to tie together, this is not the case.

Previously medical devices used by the healthcare facilities are of two types

a. Devices which can be reused multiple times after they are cleaned, inspected and sterilized

b. Devices which are disposed once they are used [1]

However the medical industry has been changed with the advent of disposable, cheap plastics being used for manufacturing all types of medical devices ranging from devices costing from few cents to thousands of dollars. In fact most of the hospitals are reusing the same devices which are meant for single use. Hence the questions arises what constitutes safe and appropriate way to reuse disposable medical devices.

Another reason for hospitals reusing some of the medical devices meant for single use is because of rising healthcare costs. Until few years back, United States has a total of nearly $2 trillion expenditures in 2004 and it is projected to increase to $4 trillion dollars by 2015. [2]

However the hospital lately have started relying on third party reprocessing firms for sterilizing, refurbishing and repackaging the devices and then resell them to the hospitals for fraction of the original

cost leading to lot of cost savings to the hospitals. Usually the job of the reprocessors are *decontamination, disassembling, cleaning, inspecting, testing, packaging, relabeling and sterilizing or disinfecting single use devices* (SUDs).Annually atleast $80 billion dollar worth of medical products are sold out of which atleast $3 billion dollar worth of medical products are for these single use devices leading to blossoming of these reprocessing firms with annual revenues exceeding $125 million dollars annually.[3]

Also the benefits of these reprocessing firms are multifold. Not only do they have the benefit of having cheaper and dependable source of medical supply for healthcare facilities, they also lead to reduction in volume of medical waste especially infectious waste. Since properly transporting wastes can be expensive, in some countries these wastes are dumped behind hospitals or clinics or partially burned in open pits leading to pollution. If hospitals start using more and more reusable disposable products, it will lead to less pollution, less incineration and less use of dump sites.[1] It has also been estimated that by using the current reprocessors' full product line, it can save $600,000 to $1 million dollars in waste and divert between 5000-15000 pounds of waste from landfills. Also these savings can help the hospitals to divert their limited resources for other uses like upgrading their technology, additional nurse hires, indigent care offerings and to improve their infrastructure.[4] Also in developing countries, most hospitals are overburdened and underfunded. By providing a dependable supply of items that only needs to be replaced periodically will lead to lot of cost savings and better healthcare [1]

1.2 Problem Statement and Rationale

With healthcare expenditure in the US reaching $2 trillion dollars and increase in medical waste, hospitals and other healthcare providers are under tremendous pressure to control costs and decrease medical wastes.[5] One of the cost-saving approach which is gaining acceptance is the reuse of medical devices, some of which are designed for single use. A growing number of third party reprocessing firms are willing to sterilize, refurbish, disassemble and/or remanufacture devices and resell them to hospitals, send them to recycling or for incinerations. Even though the reprocessing industry has made use of optimum disassembly techniques in order to generate optimum profit from

each medical device, they are met with limited success since most of the medical devices can be hard to disassemble without a change in the basic design

The main objective here is for these reprocessing firms to generate substantial profits from these devices while at the same time minimize the negative environmental impacts of these devices. What is required is a framework in place which will help to combine the optimum disassembly techniques with the modularity concept in order to come up with recommendations for redesigning a medical product which will help the reprocessing firms to disassemble these devices easier and faster thus increasing their profit potential while at the same time extract maximum material for material Retrieval or recycling purposes.

1.3 Objective of the study

The main objective of this study is to come up with a framework in order to compare the potential profits that can be obtained between the initial design and redesigned product by dealing specifically with aspects of configuration design concerned with life cycle objectives i.e. material objective (material Retrieval) and Post life objective (recycle or reprocess or incinerate). This is achieved by considering the initial configuration design of the product and calculating the profit that can be obtained with respect to the life cycle objectives

Once obtained, the device is redesigned using the CI algorithm into appropriate modules for each life cycle objective individually and for the combined objectives and profits are calculated.

Later modularity measures are used to assess the design for the combined objective and further recommendations are made for redesign efforts

1.4 CONTRIBUTION OF THE STUDY:

Current research and literature on design for disassembly deals with calculating ways to disassemble a product optimally by taking into consideration the costs and revenues that can be obtained by disassembling a product. However this approach is limited as some devices can be intrinsically difficult to disassemble which can limit the potential for recycling the product. Even when there is substantial literature recommending designing product in terms of functional modules, there doesn't exist a concrete framework which helps to combine these two concepts, especially for recycling efforts, in order to obtain optimal solutions which cannot be done by implementing design for disassembly techniques alone. This study is an attempt in that direction to come up with a framework which can help to determine clear ways to obtain modules for recycling purposes, hence making it easier to disassemble with less cost and time while at the same time fulfill its recycling goals

1.5 SCOPE AND LIMITATION

The scope of the proposed methodology is:

1. The method is implemented by calculating and comparing only the resultant profits between initial and redesigned product but not others factors that might be the basis for deciding a superior design
2. Reverse method is implemented for calculating the list of possible subassemblies
3. The disassembly process is considered to be manual
4. The approach for the architecture decomposition of the product is in terms of its subassemblies and not through connection approach

The Limitations of the methodology proposed are

1. The methodology is ideal for devices which are not too complex (as most of the medical devices are) and doesn't have too many life objectives
2. The number of life cycle objective considered are only 2 which are material Retrieval and recycling

1.6 THESIS OUTLINE

The entire study is divided into 6 chapters. Chapter 1 "Introduction" states the background of the study, the motivation to propose the methodology, its objective and its scope and limitation

Chapter 2 "Theoretical background" talks about the background and the need for finding sustainable solutions for medical devices. It also consists of concepts which are critical to consider when dealing with designing sustainable devices. This allows the reader to get familiarized with the important concepts critical for coming up with sustainable solutions. Section 2.3 starts off by explaining about the life cycle assessment and the stages that needs to be that needs to be considered for each product before implementing any techniques or methodologies. This section gives the big picture before getting into the details of implementing the methodology. Section 2.4 explains about the design for disassembly principals, one of the two critical components of the methodology, and its critical role in life cycle assessment. Table 1.3 in this section also lists the compatibility values which will be critical while considering the compatibility values for the components later. Section 2.6 gives an overview of modularity, the second critical component that needs to be considered when implementing the methodology.

Chapter 3 "Proposed Methodology" will present the methodology that needs to be followed. It includes steps for design decisions that need to be implemented for the objectives that are being considered. Once the design decisions are implemented, the profits are calculated and compared.

Chapter 4 and chapter 5 which are "Case Study 1" and "Case study 2" respectively are the case studies considered for implementing the methodology. The case study considered in chapter 4 is an Endopath Xcel trocar device while the in chapter 5, the case study considered is an Enseal Laparoscopic Device. In both these chapters, after the profits are calculated, recommendations and conclusions are made at the end of each chapter

Chapter 6 "Future Work" elaborates on the scope and limitations of the framework proposed and further research that will be required in order to the make the model more accurate and robust for complex cases

Chapter 2: Theoretical Background

2.1 Introduction

Medical products produce a lot of wastes in the form of solid, industrial and chemical wastes in developed countries. Hospitals in USA alone produce more than 6,600 tons of waste per day, including 800 tons of non-hazardous, and potentially recyclable, plastic parts. Also if not disposed properly, the hazardous chemicals and solvents used in the medical products during manufacture can be extremely harmful. Disposal of such kinds of wastes can also be costly from an environmental and financial point of view. As such, it can be quite beneficial for the medical industry to embrace sustainable design, in which products are evaluated in terms of financial, social and environmental impact as well

2.2 Medical Device Sustainability

2.2.1 Introduction

There exist a number of factors and competitive advantages by brining sustainable design to the industry. The European Union which has banned hazardous materials is promoting recycling and is encouraging energy efficiency using legislation. Standards like WEEE (Directive on Waste Electrical and Electronic Equipment), RoHS (Restriction of Hazardous Substances in Electrical and Electronic Equipment), REACH (Registration, Evaluation and Authorization of Chemicals), and the EuP regulations (Energy Using Products) which is enforced for many medical product, has gained significant support in recent years. Many experts believe it is only a matter of time before similar standards will be applied for medical products in U.S too which has lagged behind in the ratification of environment legislation. Companies in U.S by staying ahead of legislation and preparing these products according to these standards can decrease long term costs and can have significant advantage over the companies which don’t

In U.S, Group Purchasing Organizations (GPOs) and other large hospital conglomerates are showing healthy signs of using environmental friendly medical products. They are looking at the public-relations advantages in supporting such measures, besides opportunities for reducing wastes and to greatly reduce operating costs. According to advocacy groups, the cost for disposal of medical waste in 2000 was between $44 and $68 per ton. With healthcare facilities producing more than million tons of waste per year, they are spending almost $130 million per year just to move, store and incinerate the waste. To control such costs, many hospitals are moving to using eco-friendly products which are PVC-free, mercury-free and lead-free.

There are also other financial gains to be made by moving to sustainable manufacturing and design. By planning for proactive design at sustainability at the concept level itself, it will help to reduce a lot of wastes in the form of packaging and shipping. It also improves the optimum use of raw materials and manufacturing efficiency. Also to improve flexibility, zero-defect manufacturing and to eliminate over-production, tools like six sigma, Lean manufacturing and current good manufacturing process(CGMP) can be used. These tools can also be for advocating critical tenants for sustainable design.

Such practices yield environmental friendly medical products of higher quality and of low cost and is also helpful in reducing product weight, packaging, and parts counts helping manufacturers cut material cost and well as fuel for transportation. Companies when they start understanding the challenges and embrace sustainability prior to industry environmental requirements will have a competitive advantage [6]

2.2.2 Implementing Sustainable Design for Medical Devices

Although there exist various obstacles to implement sustainable design for medical devices, there exists various ways in order to circumvent those barriers.

Before implementing the design, the designer needs to develop an understanding of the entire life cycle of the product. It includes understanding all stages of the product including concept development,

material selection, design and engineering, manufacturing, packaging, transportation, use and end of life disposal. This can lead to improvement in time to market, risk reduction, efficient material and energy usage, safety and regulatory compliance, and packaging and transportation costs.

In order to map the product life cycle, various tools are available, softwares like Eco-it and Sima-Pro software, environmental impact analysis tool like Eco-indicator 99 and etc. Others include checklists, spreadsheets and flowcharts to map the product life cycle.

By designing products for easy disassembly, minimizing bulky or non-essential packaging, reducing parts, moderating the use of dissimilar materials and by eliminating toxic or hazardous material, it will help to implement sustainable design as well as reduce product size and weight helping to create compact packaging which can greatly reduce fuel consumption and decrease transportation costs. Specifically for medical products, by using only those materials which can limit environmental damage during disposal and incineration can go a long way to reduce toxic and harmful air emissions and reduce processing costs. Also by creating a durable and a disposable product by creating a repeatable interface between the components without impairing the functionality, it will help to create products with durable components and smaller disposable components. Such components can minimize waste for the disposable device business model

Along with this, by developing a materials database and cataloging applicable requirements and standards will allow for convenient access to important information. In order to track processes, material and waste, quality system requirements programs as per FDA regulations can be put in place. Complying with ISO 9000 requirements for quality management or by instituting ISO 14000 (environmental management) will help to put more management-backed emphasis on product life cycle considerations

By implementing Six Sigma and Lean Manufacturing, it will lead to low defect manufacturing and it will allow for process flexibility [7]

Table 2.1: Critical Stages for designing Sustainable Medical Device

Implementing Sustainable Design for Medical Devices
1. Look at the entire product life cycle. Use tools and softwares like Eco-it and Sima-Pro
2. Design Products for a) easy disassembly b) minimize unnecessary packaging c) reduce parts d) moderate use of dissimilar
3. Develop a material database and catalog applicable requirements and standards
4.Implement Quality System Requirements programs
5.Implement Six Sigma and Lean Manufacturing

2.3 Pressures for Finding More Sustainable Design

While safety, efficacy, and usability will always be at the forefront of design and development, there are other pressures too for finding solutions that are also more sustainable

These pressures include:

Regulatory Pressures: European Union (EU) regulations on waste reduction and use of hazardous materials have already had a big impact on product development in consumer electronics and industrial categories. While medical devices have been exempt from many of these regulations, it's only a matter of time before regulations like these are more widely adopted and applied to medical markets.

Market Pressure: As they begin to apply triple-bottom-line thinking to their businesses, more and more hospitals are beginning to use "sustainability scorecards." These scorecards factor into purchasing

decisions. A low sustainability score can mean the difference between winning or losing a multi-million dollar sale.

Social Pressures: As sustainable thinking becomes more ubiquitous, social pressures from media, consumers, and practitioners increase the call to reduce waste in general and medical waste in particular.

Corporate Pressures: Realizing that Corporate Responsibility and Sustainable practices are good business, medical device companies are adopting them. These practices will no doubt play into how these companies develop medical devices.

All these together might seem like an endless array of constraints, doomed to raise costs and bog down the process. But when it is understood that truly sustainable practices can result in lowered costs and streamlined operations, leading the charge for sustainability in medical devices presents a great business opportunity. Embracing the push toward more sustainable practices now will give a company a competitive advantage by providing product differentiation and increasing profits [7]

2.4 Life Cycle Assessment

2.4.1 Introduction

One of the most valuable insights from the sustainability arena is zooming out to a broader view as we think more systemically. The medical devices we develop cannot be considered in isolation. As we zoom out one level, Life Cycle Analysis helps us extend the view of our products from sourcing raw materials, through development, use, and finally through end-of-life disposal and recycling. But the real big picture view extends beyond typical life cycle assessments. Products exist in a larger ecosystem where cultural factors come into play.

In fact, societal fears about the spread of diseases like HIV were a key driver of the increased use of the disposables business model in the medical industry. We quickly shifted away from the old practices of reusable products (often made of glass and metal) that were sterilized between uses. Today, that paradigm has largely been replaced with disposables. From simple syringes to high-tech surgical tools, countless medical businesses have been built around the one-time-use model. Patients are

comforted by the thought that these throw-away products protect them from blood-borne pathogens. And while they do offer protection, society is increasingly realizing that a throw-away model is ultimately not optimal. Things that are thrown away cost us money to produce, they cost us in terms of hard dollars for disposal and recycling, and they cost us in environmental damage associated with landfills and incineration. The pendulum has begun to swing away from the peak where high use of disposables made the most sense. Thinking systemically helps us understand this, and helps us develop medical devices more efficiently, effectively, and appropriately.

Obviously, the disposable business model isn't going away any time soon. But even working with disposables, we can make a real difference by re-examining the medical devices we create through a lens of sustainability.[7]

2.4.2 Life Cycle Assessment Implementation Stages

Life Cycle Assessment, as defined by SETAC (Society of environmental toxicology and chemistry), is “a process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and material uses and releases to the environment; and to identify and evaluate opportunities to effect environmental improvements".[8, 9]

The methodological framework for conducting LCA, as defined by both SETAC [8] and ISO [10], comprises four main phases. The two approaches are compared below

Table 2.2: Comparison of ISO and SETAC frameworks

SETAC	**ISO-14040 [10]**
1.Goal Definition and Scoping	1.Goal and Scope Definition [11]
2.Inventory Analysis	2.Inventory Analysis [11]
3.Impact Assessment	3.Impact Assessment [12]
4.Improvement Assessment	4.Interpretation [13]

As shown in table 1.1, the framework proposed by ISO is similar to the one defined SETAC differing only in the final phase. The interactions among the LCA phases are shown in Figure 1.1

Stage 1: The first step in LCA analysis is the definition of the system under study, which is the goal definition and scoping phase. The system of interest exists because it produces goods and services, which are treated together as outputs. To generate these outputs, inputs of energy and materials are required. Here the system boundaries are drawn from `cradle to grave' to include all burdens and impacts in the life cycle of a product or a process, so that the inputs into the system become primary resources.[9]

Stage 2: Inventory Analysis

In the 2nd step, which is the Inventory Analysis, material and energy balances are performed and the environmental burdens are quantified. The burdens are defined by resource consumption and emissions to air, water and solid waste

Stage 3: Impact Assessment:

Once the burdens are identified, these burdens are aggregated into smaller number of impact categories (Classification) and their potential impacts are evaluated (Characterization). A number of methods have been suggested for the identification and quantification of environmental impacts. However, the

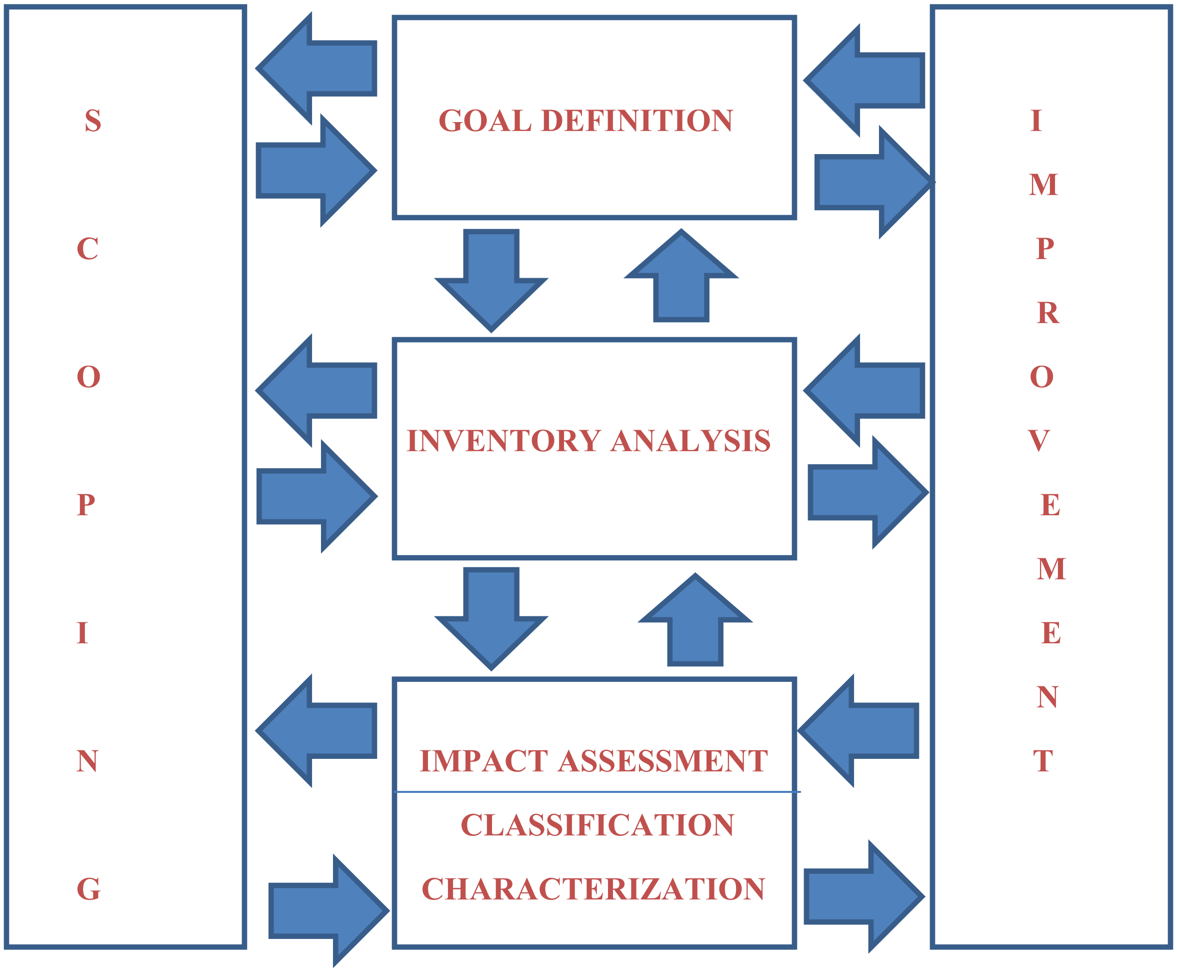

Figure 1.1: Interactions between different LCA stages

problem-oriented method, developed by Heijungs et al. [14], is the most widely used. In this approach, the burdens are aggregated according to the relative contributions to specific potential environmental effects, such as global warming potential, acidification, ozone depletion etc. For instance, CO_2 is a reference gas for determining the global warming potential of other related gases, such as CH_4 and other VOCs [15-20]

Stage 4: Improvement Assessment:

The final phase in the SETAC methodology is Improvement Assessment and is aimed at identifying the possibilities for improving the performance of the system. In the ISO methodology, this phase is known

as Interpretation and, in addition to improvements and innovations, it covers identification of major stages in the life cycle contributing to the impacts, sensitivity analysis and final recommendations [21].

Examples of LCA studies include assessment of the environmental impacts of consumer products; others are aimed at improvements of environmental performance or development of a new product or a process [22]

2.5 Design for Disassembly

2.5.1 Introduction

With changes in design trends and advancing technology, there has been a dramatic shortening of life-spans for many of today's products. This is placing heavy demand and burden on our natural and physical resources particularly during manufacture and when the products reach their end-of-life

In order to sustain such a fast rate of product-life turnover, both economic and environmental impacts needs to considered at almost every stage of the design and manufacturing process

Designers, on their part, are steadily employing techniques which will allow them to design with greater responsibility, Design for Disassembly being one of those techniques. It involves techniques of designing a product for easier maintenance, repair, Retrieval and reuse of components/materials. The tremendous opportunities being offered by Design for Disassembly has led to its increased recognition as an effective tool by designers, manufacturers and legislative boards alike

2.5.2 Pressures for Implementing DFD

Impending WEEE and RoHS legislations are pressurizing manufacturers into adopting sustainable product design principles, but designing for disassembly isn't just about meeting legal requirements.

By reducing waste in the manufacturing and Retrieval processes using DfD techniques, one can significantly reduce production costs and allow for greater technical efficiency.

Implementing DfD into a design specification allows the product and its components to be better suited for re-use or recycling when it has reached its end of life, thus reducing the scale of resources required to create new products [23]

2.5.3 Design for Disassembly Principals

To design products according to design for disassembly, the important factors that needs to be considered are

1. The selection and the use of materials
2. The design of components and product architecture
3. Use of appropriate fasteners

a) Selection of material

The most limiting factor in economic recycling of complex assemblies is the separation into pure material streams-either manually or mechanically. In order to carry out this process optimally, there must be a significant value retained in the recycled product in order for the separation to be economically feasible. This is applicable to most products which consist of different subassemblies made of different materials. Currently there exists different guidelines depending on the separation that must be carried out. As rule of thumb, products with low Material Removal Rate (MRR) – less than 2.26kg/minute for plastics – benefit from mechanical disassembly, whereas it is more economical to manually disassemble products with a high MMR (approx 4.5kg/minute)

The amount of material (grams) that has to be removed per minute for recycling to be cost-neutral for manual disassembly is as given below

Table 2.3 Material to be removed for recycling to be Cost-neutral [24]

Precious Metals		Metals		Plastics		Glass	
Gold	0.05	Copper	300	PEE	250	Glass	6000
Palladium	0.14	Aluminum	700	PC,PM	350		
Silver	5.10	Iron	50,000	ABS	800		
				PS	1000		
				PVC	4000		

Through careful selection of materials, separation time can be reduced further because components made of similar materials don't require disassembly. Other factors which influence the recyclability are materials which are compatible with compatible fixings/attachments which greatly increases the product's recyclability, while incompatible materials, non-dismountable surface attachments and factors reduces the recycling performance increasing the steps required to recycle, making it both costly and resource-intensive. However if the resources required exceed the actual material value of the product, it is not economically feasible to carry out the recycling process

In an ideal situation, the assembly would be constructed from a single material, although this is rarely case. The shortest "path" towards material recycling is the next best target, and this will largely depend on the material compatibility.

Below table breaks down the compatibility of various plastics based on their chemical structures of the materials which needs to be similar to be broken down into their raw form

However care should be taken that the materials used shouldn't compromise the structural requirements of the design. Regulated /restricted materials are suggested to be avoided or recycled whenever possible as often they have legislation stating that they must be recycled or removed from their host assemblies before disposal

b) Component Design & Product Architecture

While designing for disassembly, there are some common principals that component design and product architecture share many of the principals shared by design for disassembly. They are

1) Minimize the number of components used in an assembly either by integrating parts or through system redesign

2) Minimize the different types of materials used in an assembly

3) Separate components into modular sub-assemblies

4) Avoid using laminates which requires separation prior to re-use

5) Avoid painting parts as only a small percentage of paint can contaminate and prevent an entire batch of plastic from being recycled

c) Use of Fasteners

Fasteners play a critical role in combining the components and subassemblies. By

1) Minimizing the number of fasteners used within an assembly

2) Minimize the different types of fasteners used in an assembly

3) Standardizing the fasteners used

4) Not compromising the structural qualities of the assembly by using inadequate fasteners

5) Using snap-fits wherever possible to eliminate the need of the fastener while keeping mind the work hardening, fracture, fatigue failure and general wear of the snap-fits

6) Making it easy to access the fasteners

7) Considering the use of fasteners or those incorporating ADSM technology [24]

1= Compatible

2= Compatible with limitations

3 = Compatible only in small amounts

4 = Not compatible

Table 2.4.Compatibility of Various Plastics [24]

		ADDITIVE PLASTICS											
MATRIX MATERIAL	**Important Plastics**	**PE**	**PVC**	**PS**	**PC**	**PP**	**PA**	**POM**	**SAN**	**ABS**	**PBTP**	**PETP**	**PMMA**
	PE	1	4	4	4	1	4	4	4	4	4	4	4
	PVC	4	1	4	4	4	4	4	1	2	4	4	1
	PS	4	4	1	4	4	4	4	4	4	4	4	4
	PC	4	3	4	1	4	4	4	1	1	1	1	1
	PP	3	4	4	4	1	4	4	4	4	4	4	4
	PA	4	4	3	4	4	1	4	4	4	3	3	4
	POM	4	4	4	4	4	4	1	4	4	3	4	4
	SAN	4	1	4	1	4	4	4	1	1	4	4	1
	ABS	4	2	4	1	4	4	3	4	1	3	3	1
	PBTP	4	4	4	1	4	3	4	4	3	1	4	4
	PETP	4	4	3	1	4	3	4	4	3	4	1	4
	PMMA	4	1	3	1	4	4	3	1	1	4	4	1

2.6 End of Life Disassembly

Disassembly as a process started to gain recognition during 1990s when the number and variety of discarded complex products increased rapidly. With growing environmental consciousness, it paved the way for the introduction of take-back systems for discarded products. In various countries, a fee has to be paid in advance when the consumer bought a product which is used for take-back and subsequent environmentally conscious processing of the product after it has been discarded. Such processing includes disassembly, shredding, material separation and retrieval. This is beneficial as it saved a lot of

resources, material and land by reducing the amount of final waste that is sent to the landfill. End of life (EOL) product disassembling process is given in the figure

In the 1970s, components reuse and recycling was limited to cars as they were rich in ferrous metals which constituted almost three-fourth of the car body.

With increasing number of discarded materials like complex consumer products and medical devices, the urgency for environmentally driven end of life processing has been widely recognized. However, because of the changing composition of electronic scrap and medical device components, there has been gradual decrease in the amount of valuable materials which can be retrieved from these products which has made the recycling process less lucrative from a purely economic point of view. Also in these products, the metal components are relatively small which pushes down the economic viability for disassembly. This is in addition to the increasing variety of electronic items and sophisticated medical products and their changing designs [25]

However, the full disassembly of a product tends to be unproductive due to technical and cost constraints and product conditions after usage. Hence selective disassembly is opted for since it more practical where only a limited number of disassembly paths that lead to selected parts with recovering potential are considered, hence driving down the costs and increasing the potential profits [26]

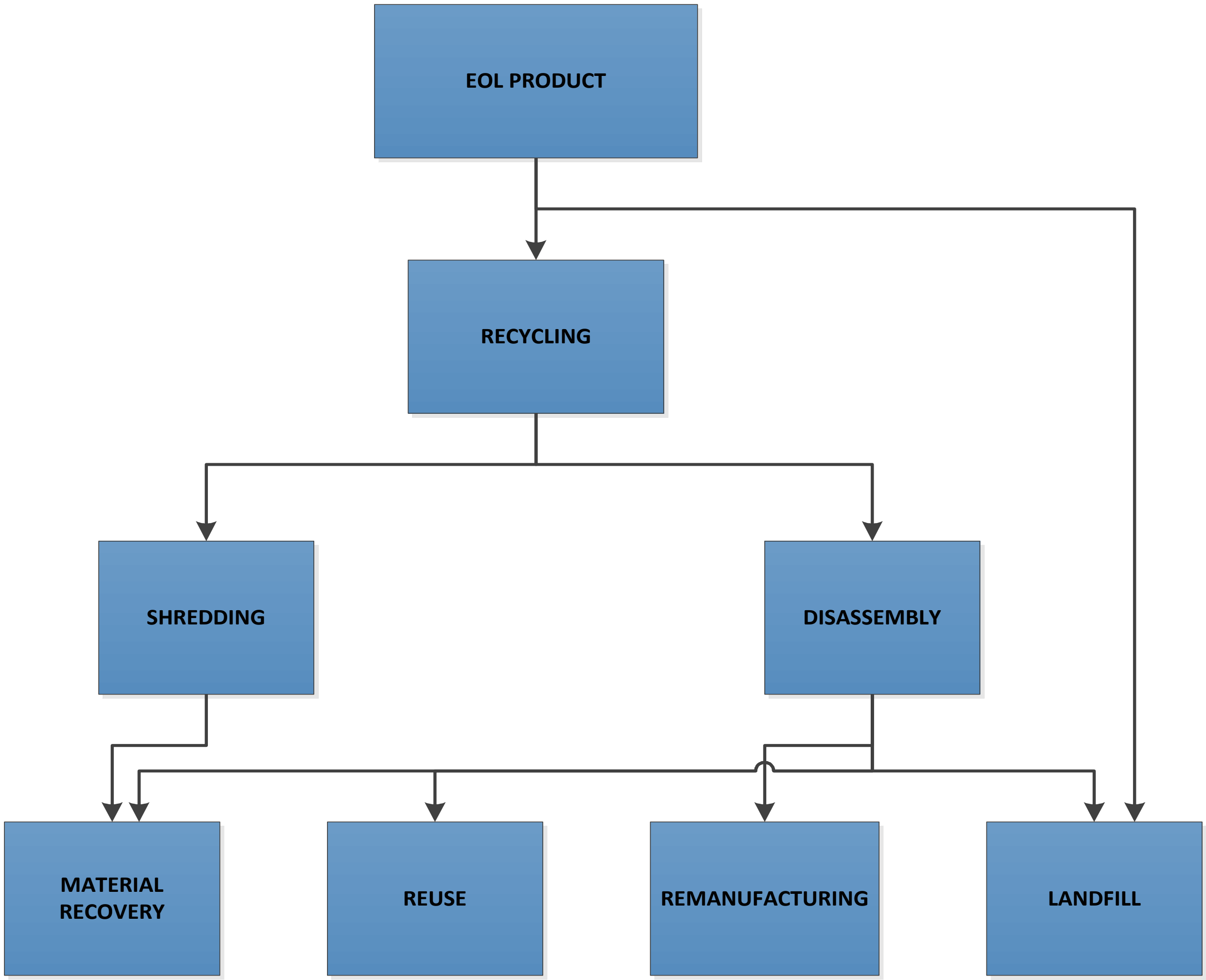

Figure 1.2 : EOL Product Disassembling [26]

However to differentiate the difference between key concepts like recycling, reuse and remanufacturing, the definitions are given below

Recycling: According to Pamela Murphy, it is a process to convert waste materials into new products, to reduce the consumption of fresh raw materials, reduce energy usage, air pollution and water pollution by reducing the need for "conventional" waste disposal, and to lower greenhouse gas emissions [27]

Remanufacture: It is a process of disassembly and recovery at the module level and component level which requires the repair or replacement of worn out or obsolete components and modules which are subjected to degradation [28]

Reuse: In its broad sense, an item is reused for the same function or for a different function. It is different from recycling because recycling involves breaking down of used item into raw materials

which are later reused to make new parts. Since reuse doesn't involve reprocessing, it more convenient as it doesn't involve additional time, money, energy and resources

2.7 MODULARITY

A module can be defined as a physical or conceptual grouping of components. Modularization, due to the functional independence that it creates, has been called the goal of good design. Often, a product's architecture is thought of in terms of its modules. For example, for a car door lock, its modules constitute its lock, window regulator, structural components, interior panel components etc.

In terms of life-cycle modularity, it entails maintaining independence between components and all life cycle processes in different modules, encouraging similarity in all components and processes in a module and maintaining interchangeability between modules

In terms of Life-cycle engineering,

a) Modular products tends to have fewer components for assembly and therefor cheaper to disassemble.
b) Also by grouping components into modules by how they are recycled will greatly reduce product retirement costs

2.7.1 Current Research

According to Ulrich and Tung (1990), based on their research, modularity is defined as the relationship between a product's functional and physical architectures such that (1) there is one to one correspondence between the functional and physical structures, and (2) unintended interactions between modules are minimized.

The goal of the modular design is to maintain independence between various functions of a product which has led to searching for connections between physical independence and functional independence

Ulrich (1995) in extension of his research has stated that a modular product or sub-assembly has "one-to-one mapping from functional elements in the function structure to the physical components of the product" and that all interfaces between the components of different modules are decoupled

The role of product architecture in modular design is discussed by Newcomb, et al. (1996) wherein they looked at the effects of modular architecture on the product life-cycle. Chang and ward

(1995), Erixson (1996) and Kusiak (1996) discuss how design for modularity can be used to decrease assembly and manufacturing costs. Chen, et al. (1994) proposes measures of modularity based upon the independence of functional requirements and sensitivity to changes in design parameters

In terms of life cycle modularity, the definition of modularity has been expanded to include one-to-one correspondence between the physical structures and structures of relevance to a life cycle viewpoint, thus helping to define modularity in terms of recycling [29]

2.7.2 Life Cycle Modularity

High life cycle modularity across multiple viewpoints of interest can be defined as the ability for designers, manufacturers, recyclers and maintenance personal to view product's structure in similar ways. For example, taking the example of car door lock, the door lock is a module from the designer's viewpoint and would be a module from the recycling viewpoint if all the components are made of similar material. Thus a structural module can correspond to manufacturing module, a recycling module and a service module.

Some of the advantages for having high modularity across multiple viewpoints are

1) Multiple views of the products wouldn't be necessary
2) Number of people involved in component/module design can be reduced
3) Design groups can operate independently
4) Assembly, disassembly and service costs can be reduced substantially [30]

A lot of firms have been trying to integrate many external sources of innovation by implement inter-organizational integration mechanisms in order to sustain supply relationships in order to spur inter-firm innovations. In this regards, modularity has received substantial attention for the benefits it provides.

Supporters of modularity claim it can improve management and outputs of the new product development (NPD) activities by a) allowing firms to easily de-couple both the design and the manufacturing of the components that constitute a product (b) Ensure an easy and well performing integration of externally supplied components into final product architecture.[31]

2.7.3 Advantages and Disadvantages of Modularity

There are many advantages associated with modular design. Some of them are

a) It helps the designer to control the changes in processes or requirements by promoting interchangeability. This advantage will allow the designer to design solutions until more information is available without delaying the development process
b) Modular design helps to reduce life-cycle costs by reducing the number of processes and by reducing repetitive processes
c) It helps to update components of a product more easily
d) It helps to increase the product variety
e) Helps to decrease the complexity of design and testing
f) Substantial decrease in order lead-time [29]

2.7.4 Case study to illustrate the advantages of Modular design

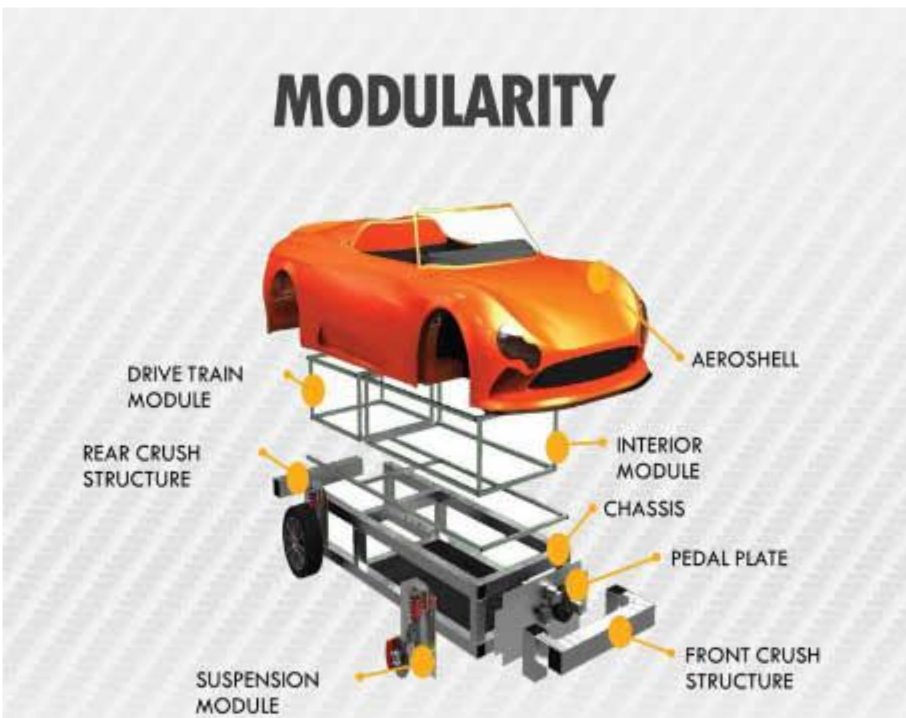

Illustration 2.1: Modular Design of a Car [32]

To illustrate the advantage of modular design, refer the above figure in which a car has been redesigned into its modular components by a company named Wikispeed which is an automotive manufacturer that produces modular cars. Among many other things, they developed a functional road-safety-legal prototype to get 100 miles per gallon in a matter of three months instead of many years that a traditional manufacturing company takes. They were able to achieve such rapid development using modular design.

Using Modular design, they were able to redesign a car into its modular components enabling them to switch a gasoline engine to an electric engine in about the time it takes to change a tire. They were also able to switch the body from a car body to a pick-up truck. It has also helped them to make changes rapidly with minimum costs through simplified modular design .It has also led to making reducing costs in tooling, in machinery and in complexity

Modular design of the car has also enabled the company to resolve problems pretty quickly. On one occasion, when they experienced a problem with a side impact test in which the team realized a four inch penetration into the cabin module, they had a team update the side impact crash structure and bolt it onto the car for that particular module in matter of days due to its simplified modular design [32]

Chapter 3: Methodology

In order to build sustainable products, one of the most important considerations is looking at its product's *Life cycle design*, in other words its cradle to grave design. This methodology specifically deals with the product decomposition in order to determine the most economical and profitable way to disassemble the product developed by using concepts of design for disassembly. Later we re-evaluate the product based on their design configurations with respect to function and post life objectives for rethinking the product architecture in terms of its modules for faster disassembly leading to usually less time and hence more profit than without its modular design. The idea to design a product with respect to life cycle objectives is initially explored by Patrick J. Newcomb et al., in their paper titled "Implications of Modularity on Product Design for the Life Cycle"

In the method that follows, the general sequence for obtaining the feasible subassemblies is to approach the architecture of the product in terms of its subassemblies and not through connection approach. Precedence relationships are obtained and converted to selection rules which apply only to subassemblies, thus selecting only those subassemblies that can be obtained by disassembly operations alone. Once the feasible subassemblies are known, AND/OR graph is defined and subsequently the disassembly sequences are determined. From the AND/OR graph, the revenue for each possible assembly and the cost for each disconnection is obtained in order to calculate the possible profit that can be obtained from each or selected subassembly [33]. For this reason, it is not necessary that the entire product needs to be disassembled but only parts which will avail us of the subassembly that can be extracted profitably. This process is known as *Partial/Selective Disassembly*.

Fig 3.1 provides the conceptual framework for implementing the methodology in order to determine the maximum profit that can be obtained through redesign according to our life cycle objectives.

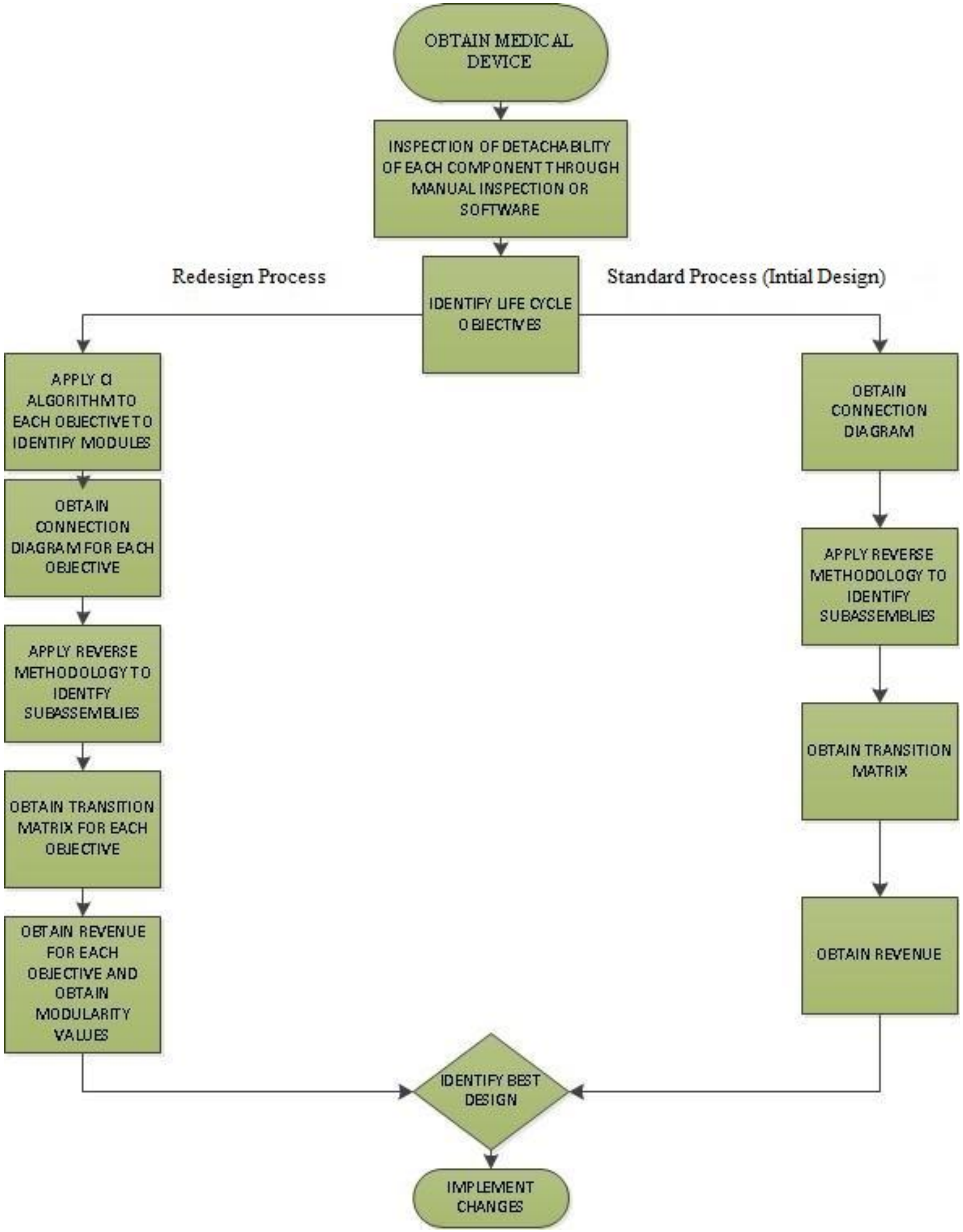

Figure 3.1 Conceptual Framework for Methodology Development

3.1 Inspection of Detachability

When a disassembly operation takes place, it is assumed that the subassembly is detached and is not obstructed and that a collision free path to infinity exists for the detachment to take place. It is also assumed that the child assembly can be moved to an infinitesimal distance with respect to the remainder of the parent assembly. Other assumptions include that the subassembly that has to be detached should be accessible by an appropriate tool and also that the subassemblies don't fall apart spontaneously.

Generally there exists two approaches to detachability, one is the *general approach* wherein through human inspection, it is determined if 2 subassemblies can be detached or not aided by software which provides the appropriate rules. The other approach is called the *restricted approach* which is confined to 1 movable product. This is done using movability and detachability information from interface matrices. This circumvents the need for sophisticated software that simulates realistic motion but uses a lot of CPU time.

For the general approach, it is assumed that the

a) Forces are absent

b) The components are rigid and not deformable

An important consequence of the assumption is that the connections between the components are determined by the dimensions, positions and orientation of the components. Another assumption is that the disassembly processes are reversible, which means, it can be assumed that the disassembly process is reversible. This implies that assembly can be considered as reversed disassembly. By including geometric constraints, this method can be used to model end of life processing, maintenance or repair and assembly optimization [33]

3.2 Identification of Objectives

Due to growing concern for the environment, the focus on designing environmentally conscious design has increased. Although recycling is one of the solution, it only part of the solution and not the whole answer. For better design the products whole life cycle needs to be considered; right from the product conceptual design to eventual disposal of the product. In the method we will be concerning

ourselves only with the aspects of configuration design concerned with Design for Assembly/Disassembly, Design for the Post-Life, as well as design for the product's intended functions. The method will be concerned with determining what components are in a design and how they are arranged spatially and logically which plays a predominant role in determining its assembly, disassembly, recycling, service and other post-life characteristics

There is a growing consensus that the product architecture ought to be thought of in terms of modularity and is regarded as a good design practice. *Modularity* has also been defined as the relationship between a product's functional and physical structures such that (1) there is a one-to-one correspondence between the functional and physical structures, and (2) unintended interactions between modules are minimized. *Modularity* is an approach that subdivides a system into smaller parts (modules) that can be independently created and then used in different systems to drive multiple functionalities. Modules are independent of one another but can communicate with each other in a loosely coupled fashion. Besides reduction in cost (due to lesser customization, and less learning time), and flexibility in design, modularity offers other benefits such as augmentation (adding new solution by merely plugging in a new module), and exclusion [34]. In this method we will be expanding the definition to allow one-to-one correspondences between physical structures and structures of relevance to a life cycle viewpoint, similar to the Pahl and Beitz concept of production-oriented modules.

This paper is concerned with the evaluation of design configurations with respect to *material and post-life objectives.* The method will attempt to come with a process that designer can use in which after evaluating the current design to come with a new design recommendations by coming up with a configuration design to determine the degree to which a design simultaneously meets its function and post-life goals. This process will involve the use of product decomposition and module comparison to achieve product modularity for which an existing decomposition algorithm is used. Measures of modularity are calculated to indicate the extent to which the product architecture achieves life cycle goals.

The specific life cycle objectives which will be evaluated in this method specific to medical devices are

• ***Material objective*** - material similarity

In order to define the degree of compatibility between different components, a value system for material retrieval objective is proposed in order to identify appropriate modules.

If a pair of components is of same material, then value of “1” is assigned to that pair of components. For example, if a device consists of different parts made of ABS (Acrylonitrile butadiene styrene), then in the matrix, those specific pair of components will be assigned “1” for their material compatibility Similarly if the materials are not of the same kind but share similar functional characteristics, like ABS and Poly (Polyacrylonitrile) which are commonly used together for building plastic products, those components are assigned “2”. Everything else is assigned a “3”

Table 3.1: Value system employed for Material Objective

Compatibility Value	Reason
1	The pair components are made of same material
2	The pair components are made of dissimilar but compatible material
3	The pair of components are both dissimilar and incompatible

• ***Post-Life objective*** - the intended destination for each component at the end of its life cycle that are being considered are: incineration, material recycling or reprocessing

Similar to material objective, parts having the same post life objective are assigned “1” as it is desirable to have modules which share the same post life objectives as it wouldn’t be necessary to disconnect them and can be removed as a whole. If the parts have similar post life objective of material reuse either through recycling or reprocessing, then those are assigned a “2”.Everything else is assigned “3”

Table 3.2: Value system employed for Post Life Objective

Compatibility Value	Reason
1	The pair components have same post life objective
2	The pair components are made of dissimilar but compatible recycling objective
3	The pair of components are both dissimilar and have incompatible

In the case studies that are going to be evaluated later, we identify subassemblies and components which can be intelligently reconfigured into modules by way of material choice and post life intent. Not every component will be included but only the major components which together can form the basic architecture of the product/device. The goal will be to figure out a configuration with good post-life intent characteristics and good material recycling characteristics while maintaining the system functionality. By that we mean that the modules and components designated for different post-life intents can be separated from one another. By that we mean the components designated for recycle should be easily separable from the ones designated for reprocessing based on two different aspects of the design:

a) the materials of the components, and

b) the connection between components since two components that are made of compatible materials need not be separated

3.3 Connection Diagram

The connection diagram is used to define the topological relationships and constraints of a product. In a connection diagram, the components and their connections represent the basic elements of

a product. The necessary information about the connections is the type of connection and the type of fastener.

The topological relationships between the components of a complete product are graphically represented using a connection diagram. A connection diagram is an undirected graph in which the nodes represent components and the arcs represent connections.

Consider figure 3.2

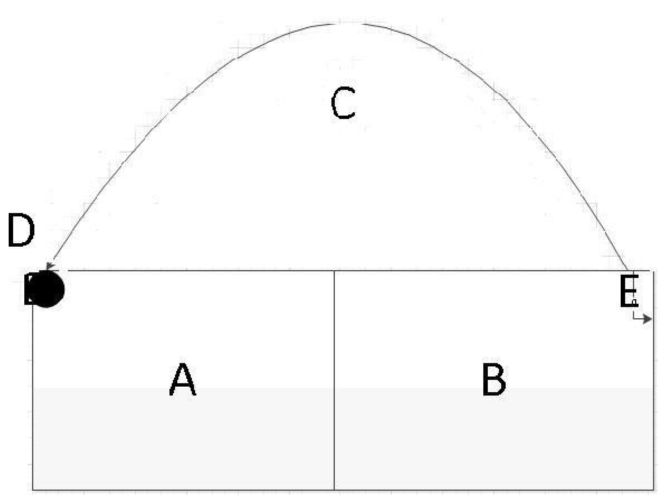

Figure 3.2 Example Demonstrating the connection diagram

We have 3 components here, which are A, B and C.A and B are mating components that are connected with a strip C.Strip C is welded to A at point D and C is screwed to B at point E. Thus D and E are fasteners. However D is known as virtual component while E is a discrete component (Navin-Chandra, 1994)

Figure 3.2 can be depicted in its extended as given in figure 3.3

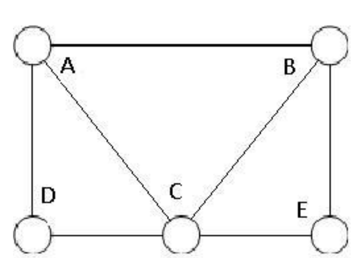

Figure 3.3 Extended Connection Diagram of the product

However here D is not a component at all and E is a quasi-component (whose Retrieval is considered not important).Therefore the connection between the components can be represented as given in figure 3.4

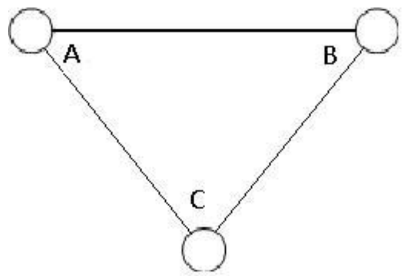

Figure 3.4 Reduced Connection Diagram of a product

However it is possible to further reduce the connection diagram if the material content of component C is considered not important or irrelevant and the strip is attached only to immobilize the 2 components, hence can be considered as a quasi-component. Therefore the connection between the components can be considered as given in figure 3.5

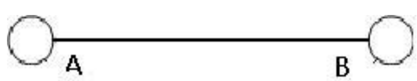

Figure 3.5 Minimal connection diagram of a product

The above rules help us to define the connection between any set of components or parts due to its inherent flexibility and arbitrariness. These rules helps us to adapt the connection diagram for any desired purpose, thus helping us to define the topological relationships critical for deriving all the possible subassemblies from a set of connected parts/components in a product.[35]

3.4 Architecture Decomposition

In this method, an architecture decomposition matrix developed by Dr Kusiak and Chow will be used to come up with appropriate module for each objective as discussed in the previous section. This method is versatile enough to handle symmetric, asymmetric and non-square matrices.

In this method, compatibility information as illustrated in the previous section will be entered in each square for the corresponding row and column parts. Through this method, it is possible to identify parts sharing compatibility by clustering "1" into their block diagonal form

The step for the method is as given below:

Step 1. Select any row i of incidence matrix M (k) (M (k) denotes matrix M at iteration k) and draw a horizontal line through it.

Step 2. For each entry "1" on the intersection with the horizontal line, draw a vertical line.

Step 3. For each entry "1" crossed by the vertical line, draw a horizontal line.

Step 4. Repeat Steps 2 and 3 until no crossed entries "1" remain. All double crossed entries "1" form a cluster.

Step 5. Transform the incidence matrix M (k) into M (k+1) by removing the rows and columns corresponding to the horizontal and vertical lines drawn in steps 1 through 4

Step 6. If matrix M (k+1) = Ø, stop; otherwise set k = k+1 and goto step 1 [30]

Example:

	A	B	C	D	E	F	G	H
A	1	1	1	2	1	2	2	3
B	1	1	1	3	1	2	3	2
C	1	1	1	3	1	2	2	2
D	2	3	3	1	2	2	2	3
E	1	1	1	2	1	3	2	3
F	2	2	2	2	2	1	2	2
G	2	3	2	2	2	2	1	2
H	3	2	2	3	3	2	2	1

Figure 3.6 Matrix with compatibility data

Consider figure 3.6 with its compatibility data. Our objective in this example is to group parts having compatibility values "1".

	A	B	C	D	E	F	G	H
A	1	1	1	2	1	2	2	3
B	1	1	1	3	1	2	3	2
C	1	1	1	3	1	2	2	2
D	2	3	3	1	2	2	2	3
E	1	1	1	2	1	3	2	3
F	2	2	2	2	2	1	2	2
G	2	3	2	2	2	2	1	2
H	3	2	2	3	3	2	2	1

Figure 3.7 At the end of 1^{st} iteration

Step 1: Select row A and draw a horizontal line through that row

Step 2: For each entry on row A, we draw a vertical line, which is through A, B C and E

Step 3: The vertical line on A intersects entries on B, C and E. Refer figure 3.7

Step 4: By repeating the above steps for other crossed entries, we obtain the matrix at the end of 1^{st} iteration as shown in figure 3.7

Step 5: Since there are no more crossed entries, the corresponding rows and columns are removed to obtain the transformed matrix as shown in figure 3.8

Step 6: Continuing the same process, the final decomposed matrix is as shown in figure 3.9

	D	F	G	H
D	1	2	2	3
F	2	1	2	2
G	2	2	1	2
H	3	2	2	1

Figure 3.8 Transformed Matrix after the 1st iteration

	A	B	C	E	D	F	G	H
A	1	1	1	1	2	2	2	3
B	1	1	1	1	3	2	3	2
C	1	1	1	1	3	2	2	2
E	1	1	1	1	2	3	2	2
D	2	3	3	2	1	2	2	3
F	2	2	2	2	2	1	2	2
G	2	3	2	2	2	2	1	2
H	3	2	2	3	3	2	2	1

Figure 3.9 Final Decomposed Matrix

The resultant matrix consists of a cluster ABCE and components D, F, G and H. This method will be employed in the case studies via software that has been developed in University of Texas at El Paso.

3.5 Connection Matrix to obtain Modules

Once the decomposed matrix is obtained, the clusters are checked for their connection feasibility via connection matrix. The connection matrix consists of cluster information in the form of highlighted clusters obtained via architecture decomposition superimposed with the connection data for each pair of

components. Each pair of components consist of an entry * if there exists a connection between them or the entry is blank if there isn't any

After the decomposed matrix has been obtained, using connection information in the form of connection matrix along with precedence constraints, modules are obtained as given below

Assume figure 3.10 is the connection matrix with the connection entries along with clusters identified from the previous result.

	A	B	C	E	D	F	G	H
A	*	*		*		*		
B	*	*		*			*	
C			*		*			
E	*	*		*	*	*		
D			*	*	*			
F						*	*	
G						*	*	*
H							*	*

Figure 3.10: The connection diagram

Looking at each module, it can be observed that connection entries for module ABCE consists of connections between A, B and E but not C. For each shaded element (i, j), the interpretation should be that the two components (i and j) are physically attached to one another. For example, in Figure 3.10, element (A, B) is marked by a * indicating that the two components are physically attached to one another via some fastening method. Note that this matrix is also square and symmetric. This scheme is meant to show which components need to be disassembled from which others in order to separate the console into its material compatible modules. Hence along this line of thought, the cluster ABCE is further divided into ABE and C

The final matrix is

	A	B	E	C	D	F	G	H
A	1	1	1	1	2	2	2	3
B	1	1	1	1	3	2	3	2
E	1	1	1	1	2	3	2	3
C	1	1	1	1	3	2	2	2
D	2	3	2	3	1	2	2	3
F	2	2	2	2	2	1	2	2
G	2	3	2	2	2	2	1	2
H	3	2	3	2	3	2	2	1

Figure 3.11 The Final Matrix

where the shaded regions are the resultant modules

3.5 Reverse Disassembly

Once the connection diagram is obtained for a device,the next step usually is to obtain the feasible assembly sequences known as the reverse subassembly approach or just REVERSE METHOD.The feasible subassembly sequences represents the parts of the assembly and the sequences between them.This method will be illustrated by taking a simple example consisting of 4 parts as given in figure 3.12.Apart from the connection diagram (figure 3.13),the formal represetation of an assembly has to be completed by a set of precedence relationships which are the formal expressions of actions that needs to be done prior to the execution of a particular action.The size of the problem,using this method,will increase polynomially by O (N^m) where N is the number of components and m is the size of the smallest subassembly

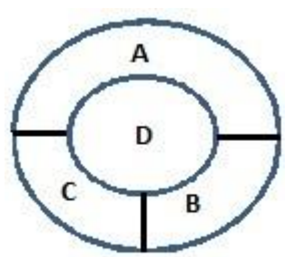

Figure 3.12 A Simple Assembly

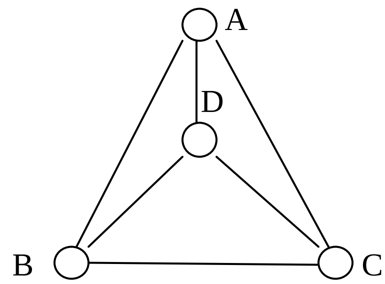

Figure 3.13 Connection Diagram for the assembly in Fig 3.14

In order to derive the feasible subassemblies and possible transitions between them, we start with 2 subassemblies, check their geometric feasibility, merge them and check the resulting 3 subassemblies, merge these with the 2 subassemblies, so on and so forth. The typical number of check that needs to be performed for each subassembly to determine their feasibility is in the order of magnitude O (K^2) where K=N-1.For the figure 3.12,the list of all 2-subassemblies,regardless of their geometric feasibility are listed in the first column.

Next, the 2-subassemblies will be checked for their geometric feasibility. If a subassembly is found to be feasible, a + symbol is placed next to it, otherwise a selection rule/precedence relationship is placed next to it. The set of precedence relations ensures there will be no deadlocks whenever they are encountered. Here in this case, removable of part D requires the removal of part A and B or B and C or A alone. A, B or C can be removed without any constraint

Table 3.3: Geometrically Feasible Subassemblies of the Product in Fig 3.14

n=2		n=3
AB	AB not D	ABD+
AC	AC not D	ACD+
AD+		BCD+
BC	BC not D	
BD+		
CD+		

Here K=N-1 =3.Hence we list columns until subassemblies with 3 components. In table 3.3, the first columns consist of all possible subassemblies regardless of their geometric feasibility. If a subassembly is feasible a + sign is placed, else a selection rule is placed next to it. In the first column, AB subassembly is infeasible which leads to the selection rule AB not D. It is similar for subassemblies AC and BC too.

Subsequently the 2 subassemblies are merged. It should be noted that the list of topologically feasible subassemblies with n=2 contains all the information that is in a connection diagram. Therefore checks on topological constraints are automatically carried out if an m-subassembly is merged with a member of a 2-subassembly that has one component in common.

AB can be merged with any 2-subassembly that includes either A or B which results in ABD and ACD. It should be noted that since AB is subjected to a selection rule, the only possible merger that can be obtained from this subassembly is ABD. The same rule applies for subassemblies AC and BC. Once the subassemblies are listed in the 2nd column for n=3, these subassemblies needs to be checked against the already obtained selection rules. Later they have to be checked for their geometric feasibility too. Proceeding along these lines, a complete list of feasible subassemblies is generated as shown in table 3.3

One of the most common examples used to illustrate this method is the Bourjault's ballpoint.

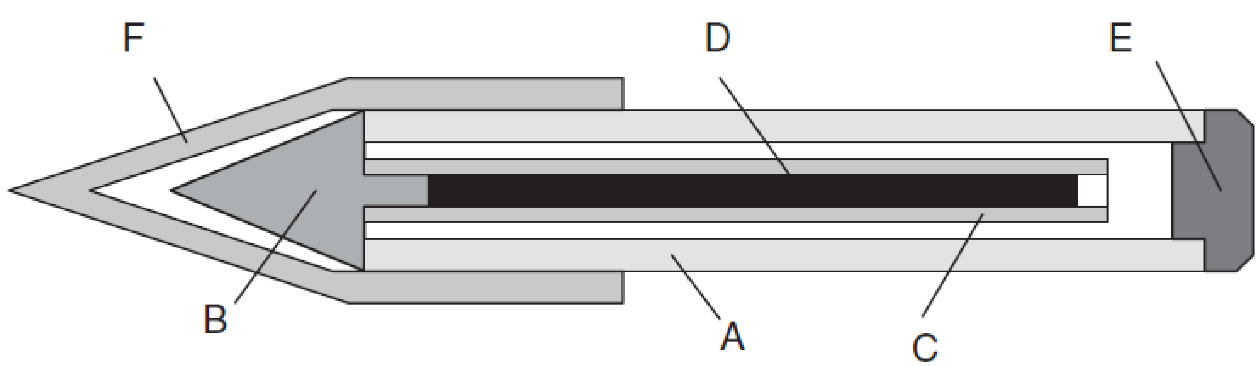

Figure 3.14: Assembly drawing of Bourjault's Ballpoint [36]

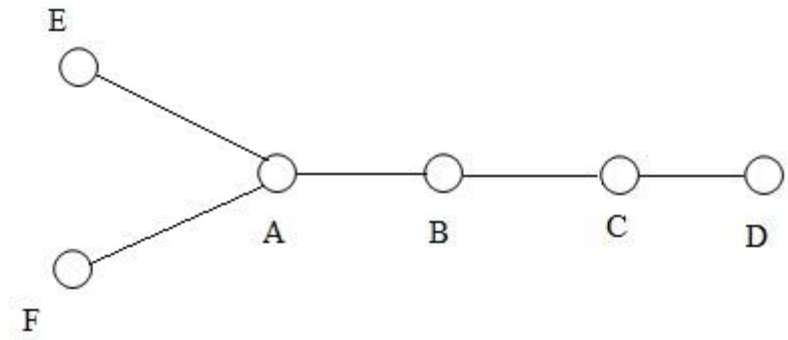

Figure 3.15: Connection Diagram for Bourjault's Ballpoint

Table 3.4: Geometrically feasible subassemblies of Bourjault's Ballpoint

n=2	n=3	n=4	n=5
AB +	ABC+	ABCD+	ABCDE+
AE +	ABE BE not D	ABCF+	ABCDF+
AF AF not B	ABF+		
BC +	BCD+		
CD+			

The Ballpoint pen consists of six components: body (A), head (B), cartridge (C), ink (D), button (E) and cap (F).Using the same methodology as above, figure 3.15 and table 3.4 gives the connection diagram and feasible subassemblies respectively

3.6 Transition Matrix

A Transition matrix helps to express the transitions of a device from its parent assembly to its child assembly. Transitions between subassemblies can take place by establishing or disestablishing definite connections between parts. A feasible transition transforms (set of) feasible subassemblies in another (set of) feasible subassemblies.

Let a (disassembly) action be a transition between a parent subassembly and two child subassemblies; such that the child subassemblies are represented by disjoint sets, while the union of the sets that represent the child subassemblies forms the set that represents the parent subassembly. When, for instance, the parent subassembly consists of three parts A, B and C, it is represented by the set {A; B;C} or short ABC: A transition from ABC to the child subassemblies AB and C fits the requirement of being an action. A prerequisite for the feasibility of that action is the feasibility of both the subassemblies ABC, AB, and C. Besides this, feasibility of an action requires that the feasible transition can be performed without being obstructed by other parts.

With this in mind, the optimal disassembly problem can be formulated as follows:

Let the disassembly problem be characterized by I feasible subassemblies and J feasible transitions between these subassemblies. The transition matrix T of the size I × J is defined such that an element Tij equals -1 if action j destroys the (parent) subassembly i, and an element Tij equals +1 if action j creates the (child) subassembly i. All the other elements equal zero. An initial and virtual action is added to the set of actions. This action represents the setting available of the original assembly

n=1	n=2	n=3
A	AB	ABC
B	BC	
C	CA	

Figure 3.16 Feasible Subassemblies

Let us consider a simple assembly ABC wherein each part can be disconnected without affecting the connection between the other 2 components. The disassembly graph is depicted such that it provides a minimal complexity without introducing ambiguities. This is obtained by depicting only one arc from the hyperarc that belongs to an action, as the other arc follows straight from the complementary structure. For instance, the hyperarc that represents action 1 points from ABC toward both AB and C. Only the branch that points to AB is depicted because the other branch follows automatically, as AB and C are complementary to each other with respect to ABC: For the same reason, the final subassemblies, i.e. the parts A, B, and C are not depicted as well

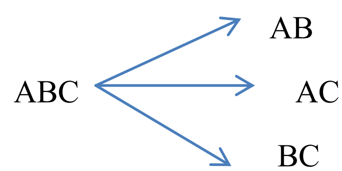

Figure 3.17 Disassembly Graph

Using Fig 3.16, the elements Tij of the transition matrix for the example given in fig 3.17 can be listed straightforwardly, see Table 3.5. The rows represent the feasible subassemblies, and the columns represent the feasible actions. One can verify from the table which transition corresponds to every action. Action 2, e.g. represents the transition from the parent subassembly ABC to the child subassemblies A and BC, according to Fig 3.17

Table 3.5 Transition Matrix for ABC assembly

	0	1	2	3	4	5	6
ABC	+1	-1	-1	-1			
AB		+1			-1		
AC			+1			-1	
BC				+1			-1
A				+1	+1	+1	
B			+1		+1		+1
C		+1				+1	+1

3.7 PROFIT CALCULATION

Apart from formalized data on the assembly's structure, which are condensed in the transition matrix, data on the costs of each action for each subassembly is required

In this paper, since it is the intention to extract a particular set of components from a particular device, the revenue from those set of components together will be assumed to be 100 and zero for the remaining.

Therefore by applying the below formula to the transition matrix, we obtain the profit that can obtained

Profit from the device = Revenue from a set of desired components $-\sum C_j X_j$

where xj be a variable that checks whether or not a specific action is performed. It equals 1 if action j is performed, and it equals 0 if action j is not performed. This information is derived from the transition matrix where all feasible actions are tabulated and we select only those actions which will help us to derive our required subassemblies (or) components

3.8 MODULARITY MEASURES

Complete modularity is achieved when there is one-to-one correspondence between the physical and the functional architectures and it has 2 aspects to it. In other words, these measures are primarily used to calculate the degree of compliance between different objective architecture and to calculate the number of connections between the components which affects the modularity. With these measures, a designer can make intelligent decisions to reduce the number of different materials by intelligently clustering compatible materials and to decrease the number of connections helpful for easier disconnection.

There are 2 measures which are used primarily to calculate modularity, which are a) Correspondence Ratio and b) Cluster Independence

Correspondence Ratio is a measure to calculate how well modules from different viewpoints correspond. It is a measure where |X| indicates the cardinality (number of elements) of set X. If the correspondence between two modules is high, CR is close to 1, while if correspondence is low, CR is close to 0.

$CR = | Vi\ (x) \cap Vj\ (x) / Vi\ (x) \cup Vj\ (x) |$

However CR measure by itself doesn't give you a good measure of the modularity since it doesn't allow us to compare two designs very well since the different designs may have considerably different modules. A better measure is to calculate the average CR for all the modules in the product called CRoverall where

$$CRoverall = \sum CRi\ /\ \#Modules$$

When CRoverall approaches zero, it means there is less correspondence between the viewpoints and when CRoverall approaches unity, it means there is more correspondence between individual modules.

Cluster Independence (CI), which is a second property of modularity, measures the dependency between the modules which exists in the form of physical connections between the modules. It measures the ratio

of intra-module connections to the total number of connections in the product. This can be measured by counting those that are in blocks along the matrix diagonal of a decomposed matrix.

Cluster Independence (CI) = #on_block_diagonal_connections / #total_connections

CI approaches 1 when most/all the links are on the block diagonal which means there are minimum/no inter-module connections in the product. In other words all the modules are disjoint, hence several products. When it approaches 0, it means each module consists of only 1 product.

Once CI and CRoverall are obtained, a modularity measure proposed by Patrick J. Newcomb and et al can be used to measure the modularity of the product [30]

Modularity = (CRoverall)*(CI)

Chapter 4: Case Study 1

This chapter presents one of the two examples using the proposed methodology for maximizing the profit and critical parts retrieval by redesigning the product. The example used is from the medical industry manufactured by Ethicon Endo Surgery, which is part of the family of companies of Johnson & Johnson. The first device that will be used as an example is the ENDOPATH XCEL trocar

4.1 DESCRIPTION

A trocar is a medical instrument which is used inside a hollow cylinder to introduce itself into the blood cavities or blood vessels. They are also used to introduce ports in the abdomen during laparoscopic surgeries. It functions as a portal for the subsequent placement of other devices, such as a chest drain, intravenous cannula, etc.

They are used to perform laparoscopic surgeries (aka key hole surgeries).They are deployed as a means of introduction for cameras and laparoscopic hand instruments, such as scissors, graspers, etc., to perform surgery hitherto carried out by making a large abdominal incision

A trocar is disclosed which includes a housing assembly and a cannula assembly attached to the housing assembly to define an axial bore therethrough. The trocar further includes an obturator assembly which slidably engages the axial bore defined by the cannula assembly. The obturator assembly includes a shaft having a piercing end for insertion into a patient and a handling end for gripping by a surgeon. Attached to the piercing end of the shaft is a piercing tip having an upper face and a lower face which taper away from the shaft to form a non-conical, blunt head. The piercing tip further includes wing elements located on opposite sides of the piercing tip between the upper face and lower face. These wing elements have lateral edges

Except where noted otherwise, the materials utilized in the components of the trocar system generally include materials such as either ABS or polycarbonate for housing sections and related

components and stainless steel for components that are required to cut tissue. A preferred ABS material is CYCOLAC which is available from General Electric. A preferred polycarbonate material is also available from General Electric under the trademark LEXAN. An alternative polycarbonate material which may be utilized is CALIBRE polycarbonate available from Dow Chemical Company. The polycarbonate materials may be partially glass filled for added strength

The trocar consists of 8 major components which are:

1. Obturator Housing
2. Support Tube
3. Shield Nose
4. Obturator Member
5. Control Knob
6. Left Flang
7. Right Flang
8. Cutting Blade

4.2 IDENTIFICATION OF OBJECTIVES

The 2 main objectives we are considering in this case are

a) Material Retrieval and

b) Good Post Life Intent

In order to apply the methodology, below is the exploited view of the trocar body. In table 4.1, the parts are listed along with what kind of material it is made of and its post life destination (recycle, reprocess or incineration)

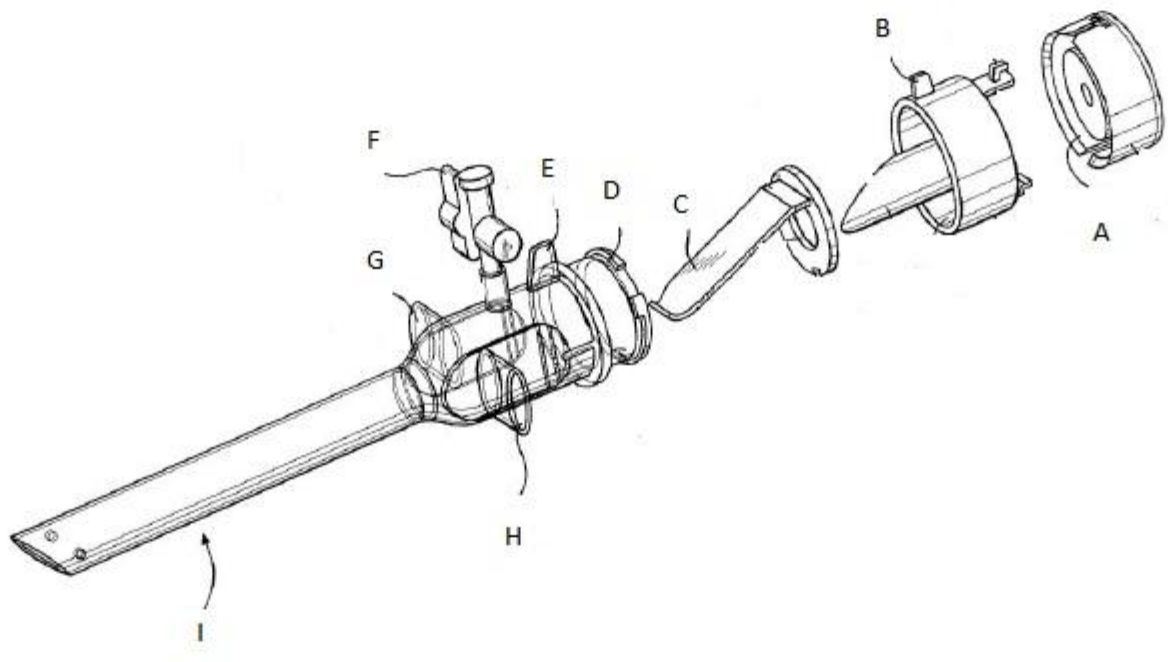

Figure 4.1 Exploited View of the Trocar

In this disassembly-to-order problem, it consists of 2 major steps in order to compare them

1. In the Standard Process, costs will be calculated to recover ABS material (material Retrieval objective) and parts meant for RECYCLING (post life objective) according to the initial design
2. Once the values are calculated, the product will be redesigned according to material Retrieval and post life objectives and costs will be calculated along with modularity measures which will serve as an index of how good the redesign effort has been in relation to the objectives and if there is any more room for improvement

Table 4.1: Trocar component's Material and their Post life Intent

Component	Material	Post Life Intent
A.Obturator Housing	ABS	Recycle
B.Support Tube	ABS	Recycle
C.Shield Nose	POLY	Incinerate
D.Obturator Member	POLY	Reprocess
E.Connector	ABS	Reprocess
F.Control knob	ABS	Reprocess
G.Left Flang	ABS	Reprocess
H.Right Flang	ABS	Reprocess
I.Cutting Blade	Stainless Steel	Reprocess

4.3 BEFORE REDESIGN

4.3.1 Connection Diagram and Feasible Subassemblies

The first step before calculating anything is to obtain the connection diagram of the product which gives the topological relations and constraints of the parts of the product. For figure 4.1, below is the connection diagram that is obtained

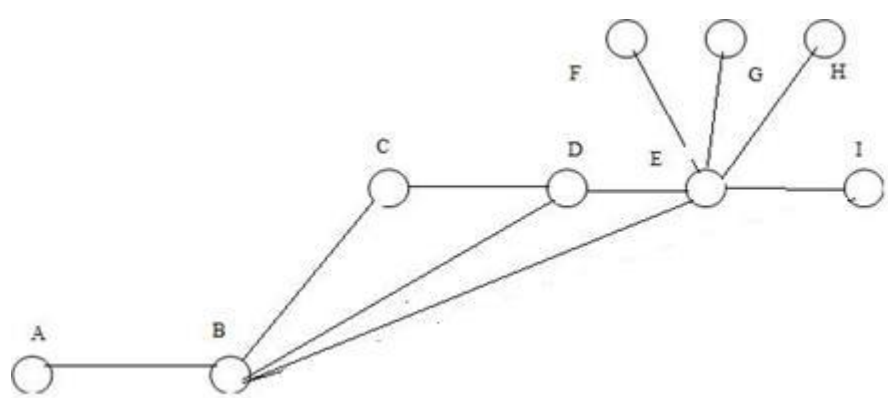

Figure 4.2 Trocar Connection Diagram before Redesign

Once the connection diagram is obtained, using reverse methodology, we try to obtain all the feasible subassemblies. Using this method, one simply starts with the 2 subassemblies, checks these for geometric feasibility, merges these, checks the resulting 3-subassemblies, merges these with the 2 subassemblies and etc. The method proceeds as follows

First we list all the 2 subassemblies regardless of their geometric feasibility from the connection diagram. In this case, K=N-1=8 where K is the subassembly with maximum number of parts possible and N is the number of parts. These are listed in the first column.

Next we will check the 2 subassemblies for their geometric feasibility from figure 4.1. If a subassembly is feasible, a + symbol is placed next to it, else, a selection rule is placed next to it.

For example, we look at combination BD and check for its geometric feasibility. Clearly B and D cannot exist together as a subassembly without C. We can translate the precedence relationship as BD not C which reads as BD cannot exist without C.

The set of selection rules guarantees that no deadlocks are encountered. It also helps to reduce the size of the problem. We note that nine out of eleven 2-subassemblies are possible.

Subsequently the 2 subassemblies are merged. It is important to note that the list of topologically feasible subassemblies with n=2 contains all the information in the connection diagram and from hence forth, the connection diagram doesn’t have to be referred to check for their topological feasibility.

BC can be merged with any 2-subassembly that includes either B or C which results in BCD, BCE and BCG. Note that BD is subjected to selection rule and the only possible merger is BCD that can be obtained from this subassembly. Once the possible mergers are obtained, they are checked against already obtained selection rules. Later they are checked for their geometric feasibility which results in rejection of BCE and BCG and the addition of an associated selection rule

Proceeding along these lines, by merging the subsequent subassemblies with 2-subassemblies, a complete list of feasible subassemblies are generated

Below is the table which contains all the possible subassemblies

Table 4.2: Geometrically Feasible Subassemblies of the Product of Fig 4.1

n=2	n=3	n=4	n=5	n=6	n=7	n=8	
AB+	ABC+	ABCD+	ABCDE+	ABCDEF+	ABCDEFG+	ABCDEFGH+	ABCDEFGHI+
BC+	BCD+	ABCE CE NOT D	ABCDG DG NOT E	DEG+	EFH+	FGI+	
CD+	BCE CE NOT D	ABCG CG NOT D	BCDEF+	DEH+	EFI+	FHI+	
DE+	BCG CG NOT D	BCDE+	BCDEG+	DEI+	EFG+	GHI+	
EF+	CDE+	BCDG DG NOT E	BCDEH+	BCDEFG+	EGI+	BCDEFGHI+	
EG+	DEF+	CDEF+	BCDEI+	EFH+	EHI+		
EH+	DEG+	CDEG+	CDEFG+	EFI+	BCDEFGH+		
EI+	DEH+	CDEH+	CDEFH+	EGH+	EFGI+		
BD BD NOT C	DEI+	CDEI+	CDEHI+	EGI+	EFHI+		
BE BE NOT C	EFG+	DEFG+	CDEGH+	EHI+	EGHI+		
BG BG NOT C	EFH+	DEFH+	CDEGI+	CDEFGH+	CDEFGHI+		
	EFI+	DEFI+	CDEFI+	EFGI+			
	EGH+	DEGH+	DEFGH+	EFHI+			
	EGI+	DEGI+	DEFGI+	EGHI+			
	EHI+	DEHI+	DEFHI+	FGHI+			
		EFGH+	DEGHI+	DEFGHI+			
		EFGI+	EFGHI+				
		EFHI+					
		EGHI+					

* BD not C => BD subassembly cannot exist without C

4.3.2 Obtaining Transition Matrix for each objective

To obtain the transition matrix, let us consider one objective at a time

a) For Retrieve ABS:

From figure 4.1 and table 4.1, the parts made of ABS which needs to be recovered is given below

Table 4.3: First Objective components that needs to be recovered

Component	Material
A.Obturator Housing	ABS
B.Support Tube	ABS
E.Connector	ABS
F.Control knob	ABS
G.Left Flang	ABS
H.Right Flang	ABS

The objective here is to calculate the cost it incurs to recover this material from the device. From the table it is clear that we need to extract components A, B, E, F, G and H.

In order to derive the disassembly sequence, the method to be followed is as given below

a) Look if all or as many of these components exist as a subassembly in the feasible subassemblies table

b) Starting from the end product, look for transitions in order to extract those subassemblies and the remaining components with minimum number of transitions between them

In order to do that we need to check table 4.2 to see if the constituent parts exist as a subassembly which consist of most number of required parts or individual components. Once identified we look for the different disconnecting sequences and select the sequence which has the least number of disconnections

From the table, only 1 sequence can be mapped which recovers the required material.

Below is the AND/OR representation of the disassembly process. The components that are required are highlighted in red

Figure 4.3: AND/OR disassembly representation for recovering ABS from Initial Design

We can see from the table that ABEFGH subassembly doesn't exist. Hence we look for the subassembly column closest to the final product which has the most number of required parts.

The possible subassemblies which can be extracted are AB and EFGH, as these are possible subassemblies, as given in the table 4.2. Between the final product and the subassembly EFGH, one possible sequence is obtained which happens to recover module AB too. Table 4.4 gives you the list of disconnections that needs to be made in order to recover the required material.

Table 4.4 is the transition matrix obtained for the selected sequence and it requires 3 transitions/disconnections from the final product to the components required as given below. Along with the required parts, we also obtain B, C and I parts too

Table 4.4: Transition Matrix for components obtained from Figure 4.3

	0	1	2	3
ABCDEFGHI	+1	-1		
CDEFGHI		+1	-1	
EFGHI			+1	-1
EFGH				+1
AB		+1		
CD			+1	
I				+1

b) To Retrieve Reprocessable material:

From figure 4.1 and table 4.1, the parts made of Reprocessable material which needs to be recovered are given below

Table 4.5: First Objective components that needs to be recovered and their material

Component	Material	Post Life Intent
D.Obturator Member	POLY	Reprocess
E.Connector	ABS	Reprocess
F.Control knob	ABS	Reprocess
G.Left Flang	ABS	Reprocess
H.Right Flang	ABS	Reprocess
I.Cutting Blade	Stainless Steel	Reprocess

The objective here is to calculate the cost it incurs to recover this material from the device. From the table it is clear that we need to extract components D, E, F, G, H, I. In order to do that we need to check table 4.2 to see if these parts exists together as a subassembly or any other possible combinations with minimum number of disconnections. Starting from the end product, we obtain the sequence which needed to extract the required components with minimum number of disconnections

Below is the AND/OR representation of the disassembly process

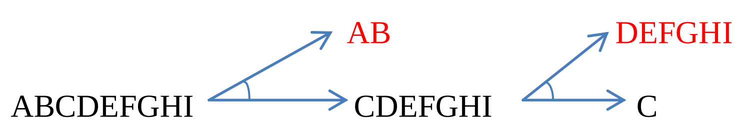

Figure 4.4: AND/OR disassembly representation for recovering Reprocessable Material from Initial Design

Below is the transition matrix that is obtained from the above disassembly process

Table 4.6: Transition Matrix obtained for Figure 4.4

	0	1	2
ABCDEFGHI	+1	-1	
CDEFGHI		+1	-1
DEFGHI			+1
AB		+1	
C			+1

We can see from the table that DEFGHI exist as a subassembly doesn't exist. The only possible subassembly with least number of disconnections is first disassociating subassembly AB and later component C. It should be noted that we were able to disconnect AB as a single subassembly but not by disconnecting A and B sequentially because AB exists as a subassembly, as given in table 4.2

Table 4.6 gives you the list of disconnections that needs to be made in order to recover the required material.

4.3.3 Calculation of Resultant Profits

A simplified cost vector is introduced in the model. Costs are assigned as given below

Table 4.7: Cost vector being assigned

Operation	**Costs**
Single Disassembly	9.4
Parallel Disassembly/Module Disassembly	9.8

As shown in the table 4.7, apart from the removal of single parts, parallel disassembly has to be considered too. For simplicity purposes, we assign 9.4 for removing each single part and 9.8 for each parallel disassembly.

Along with the cost vector, we also need to assign the revenue vector and calculations will be carried out by considered a revenue of 100 for all desired modules and zero for the remaining

a) For Retrieving ABS,

The transition matrix 4.4 is the only feasible sequence which helps to recover the ABS material. By applying the formula to the transition matrix, we obtain

Possible Profit from the desired Module $-\sum C_j X_j = 100 – [(9.8 * 2) + 9.4] = 71$

b) To Recover Reprocessable Material

The transition matrix 4.6 is the only feasible sequence which helps to recover the ABS material. By applying the formula to the transition matrix, we obtain

Possible Profit from the desired Module $-\sum C_j X_j = 100 – (9.8 + 9.4) = 80.8$

Hence the maximum possible profit that can be obtained before redesign for the 2 objectives that we have considered is given below

Table 4.8: Maximum Profit that can be obtained before Redesign

Objective	**Profit**
Recovering ABS	71
Recover Reprocessable Material	80.8

4.4 Redesigning the Device

The information given in Table 4.1 will be used to determine the modules (sets of components that share a common characteristic) that exist for different objectives. For instance, for material

Retrieval objective, the ideal design would have all the components made of a single material since the product would not need disassembly and could just be reprocessed as it is. For such pair of components, we assign a value of “1”.It is preferred that all components are made of materials compatible for recycling.

For components with compatible but different materials, they should be grouped together and a value of “2” is assigned. For other incompatible materials, a value of “3” is assigned
The objective here is the idea that compatible components should be connected to one another so that they form a structural module as well as a material compatibility module. The material compatibility matrix for the device is shown in figure 4.3. Entries in the matrix were based on compatibility data discussed above.

The rule for decomposition of the material compatibility matrix is to cluster the 1’s (good compatibility measures) into block diagonal form. To accomplish this, we derive another matrix from the material compatibility matrix, in this case given in figure 4.4,wherein we replace all pair of components with value of “1” with * since we are interested to cluster such components

4.4.1 Material Retrieval

For Redesign, we initially consider each objective. For each objective, we obtain the compatibility matrix which is derived by mapping the compatibility of each part with every other part on a scale of 1-3 hence obtaining a square matrix. Once the matrix is decomposed, the resultant matrix’s clusters (represented by the shaded region) are mapped onto a connection matrix which has the data of all the connections between the various components in order to obtain feasible modules. This process is repeated for each objective individually and the objective combined in order to obtain optimum module composition for each case.

From the results, connection diagram is obtained for each case and using reverse methodology feasible subassemblies are obtained. Simultaneously we calculate the modularity measures for each case which helps us to estimate the degree to which one objective architecture is differing from the other objective architecture. From the obtained feasible subassemblies, profits are calculated and these results are compared with the profits obtained for each objective before redesign in order to estimate potential savings.

Also from the modularity measures, we can look for improvements that can be made to increase the degree of compliance of different objectives with each other

Figure 4.5 is the material compatibility matrix that is derived from table 4.1 for the first objective. Once the values are obtained, the objective is to cluster the 1's (good compatibility measures) by employing the algorithm developed by Dr Kusiak and Chow to come up with appropriate module via CI software developed at University of Texas at El Paso

	A	B	C	D	E	F	G	H	I
A	1	1	2	2	1	1	1	1	3
B	1	1	2	2	1	1	1	1	3
C	2	2	1	1	2	2	2	2	3
D	2	2	1	1	2	2	2	2	3
E	1	1	2	2	1	1	1	1	3
F	1	1	2	2	1	1	1	1	3
G	1	1	2	2	1	1	1	1	3
H	1	1	2	2	1	1	1	1	3
I	3	3	3	3	3	3	3	3	1

Figure 4.5: Material Compatibility Matrix

Figure 4.6 shows the screenshot of solving the matrix using CI program software developed at University of Texas at El Paso. Here since the objective is to cluster all the 1's,we enter X for each pair of components which has the value X. In the software, all the row components are numbered from C1-C9 and column from A1-A9 which is unique to the software. Hence when entering the values in the

software, value in A1-C1 is entered based on the value in A-A from the matrix in figure 4.5, value in C3-A3 is entered based on value in C-C from the matrix, so on and so forth. In other words, numerical values in the software can be equated to alphabetical value in the compatibility matrix i.e. 1 is equivalent to A,2 is equivalent to B, so on and so forth

	A1	A2	A3	A4	A5	A6	A7	A8	A9
C1	X	X			X	X	X	X	
C2	X	X			X	X	X	X	
C3			X						
C4				X					
C5	X	X			X	X	X	X	
C6	X	X			X	X	X	X	
C7	X	X			X	X	X	X	
C8	X	X			X	X	X	X	
C9									X

Figure 4.6 Screenshot of the matrix before decomposition

	A1	A2	A5	A6	A7	A8	A3	A4	A9
C1	X	X	X	X	X	X			
C2	X	X	X	X	X	X			
C5	X	X	X	X	X	X			
C6	X	X	X	X	X	X			
C7	X	X	X	X	X	X			
C8	X	X	X	X	X	X			
C3							X	X	
C4							X	X	
C9									X

Figure 4.7 Screenshot of the clusters obtained after matrix decomposition

Mapping the results obtained onto the compatibility matrix, below are the clusters that are obtained as shown in figure 4.8

	A	B	E	F	G	H	C	D	I
A	1	1	1	1	1	1	2	2	3
B	1	1	1	1	1	1	2	2	3
E	1	1	1	1	1	1	2	2	3
F	1	1	1	1	1	1	2	2	3
G	1	1	1	1	1	1	2	2	3
H	1	1	1	1	1	1	2	2	3
C	2	2	2	2	2	2	1	1	3
D	2	2	2	2	2	2	1	1	3
I	3	3	3	3	3	3	3	3	1

Figure 4.8 Clusters obtained for Material Retrieval objective

Once the decomposed matrix is obtained, keeping the module representation (represented by the shaded region) intact, we map the connection between the components. In this way we might have to further divide the modules based on the connection diagram and precedence constraints in order to obtain feasible modules

The connection matrix is as given below. Once the clusters are obtained, the connection between each component is examined and they need to be divided into further clusters if there doesn't exist a connection between them or if there is any precedence constraints. The connection matrix is given in figure 4.9.Examining the connections only within the clusters, it can be observed that there is the components which are physically connected to each other form a matrix which is square and symmetric. For example, examine column A and B, there exist a square matrix within the cluster region. It is similar for columns B and E; E and F; E and G; and E and H. However there exist 2 precedence constraints; BE not C, BG not C from table 4.2. Since C exists outside the cluster, B cannot exist as a part of the module. Using that information, the clusters are further divided into the final modules as shown in figure 4.10

	A	B	E	F	G	H	C	D	I
A	*	*							
B	*	*	*				*	*	*
E		*	*	*	*	*		*	*
F			*	*					
G			*		*				
H			*			*			
C		*					*	*	
D		*	*				*	*	
I		*	*						*

Figure 4.9 Connection Diagram

Hence the final matrix is as given below

	A	B	E	F	G	H	C	D	I
A	1	1	1	1	1	1	2	2	3
B	1	1	1	1	1	1	2	2	3
E	1	1	1	1	1	1	2	2	3
F	1	1	1	1	1	1	2	2	3
G	1	1	1	1	1	1	2	2	3
H	1	1	1	1	1	1	2	2	3
C	2	2	2	2	2	2	1	1	3
D	2	2	2	2	2	2	1	1	3
I	3	3	3	3	3	3	3	3	1

Figure 4.10 Modules obtained for Material Retrieval objective

4.4.2 For Post Life Objective

Similar to the previous objective, the same process is followed for this objective too

Below is the Post-life compatibility matrix that is derived from table 4.1 for the second objective and its resultant matrix in figure 4.11

	A	B	C	D	E	F	G	H	I
A	1	1	3	2	2	2	2	2	2
B	1	1	3	2	2	2	2	2	2
C	3	3	1	3	3	3	3	3	3
D	2	2	3	1	1	1	1	1	1
E	2	2	3	1	1	1	1	1	1
F	2	2	3	1	1	1	1	1	1
G	2	2	3	1	1	1	1	1	1
H	2	2	3	1	1	1	1	1	1
I	2	2	3	1	1	1	1	1	1

Figure 4.11 Post Life Compatibility Matrix

Figure 4.12 shows the screeshot of solving the matrix using the CI program developed by University of Texas at El Paso

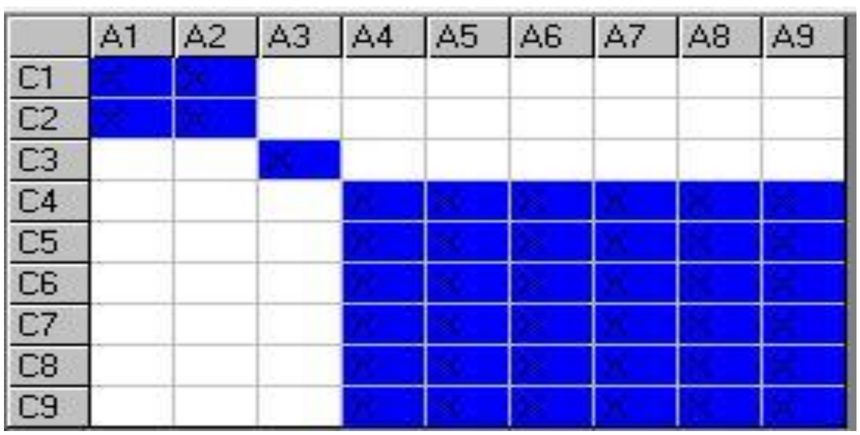

Figure 4.12 Screenshot of the clusters obtained using CI software

Hence the decomposed matrix which is represented by figure 4.12 is given below

	A	B	C	D	E	F	G	H	I
A	1	1	3	2	2	2	2	2	2
B	1	1	3	2	2	2	2	2	2
C	3	3	1	3	3	3	3	3	3
D	2	2	3	1	1	1	1	1	1
E	2	2	3	1	1	1	1	1	1
F	2	2	3	1	1	1	1	1	1
G	2	2	3	1	1	1	1	1	1
H	2	2	3	1	1	1	1	1	1
I	2	2	3	1	1	1	1	1	1

Figure 4.13 Clusters Obtained

Once the clusters are obtained, keeping the module representation (represented by the shaded region) intact, we map the connection between the components. In this way we have to further divide the clusters based on the connection diagram and precedence constraints in order to obtain feasible modules as obtained in Figure 4.1

Below is the connection diagram

	A	B	C	D	E	F	G	H	I
A	*	*							
B	*	*	*	*	*				*
C		*	*	*					
D		*	*	*	*				
E		*		*	*	*	*	*	*
F					*	*			
G					*		*		
H					*			*	
I		*			*				*

Figure 4.14 The Connection Diagram

The resultant modules is similar to the clusters obtained in figure 4.13.Hence the resultant modules for post life objective is similar to the clusters obtained in figure 4.12

4.4.3 For Combined Objectives (Material and Post life)

After it has been determined how the device can be redesigned into appropriate modules for each objective alone, now the objectives will be combined in order to redesign the product complying to both the objectives at the same time.

In this case similar procedure will be followed to obtain the desired modules. However we obtain the compatibility matrix by mapping the compatibility of each part with regards to both the objectives as given in table 4.1 with every other part on a scale of 1-3 hence obtaining the final compatibility matrix. These values are obtained based on the lowest value (1 is highest and 3 is lowest) while comparing each part with every other part based both on material compatibility and post life objective data together. The final combined objective compatibility value is obtained as given below. The values are obtained based on the least value (1=high compatibility, 3=least compatible) obtained in either of the 2 objectives, based on material and post life, for each pair of components

Table 4.9: Value System employed for combined objective

Material Compatibility	Post Life	Combined Objective
1	1	1
1	2	2
1	3	3
2	1	2
2	2	2
2	3	3
3	1	3
3	2	3

3	3	3

The final matrix is given in figure 4.15 as given below

	A	B	C	D	E	F	G	H	I
A	1	1	3	2	2	2	2	2	3
B	1	1	3	2	2	2	2	2	3
C	3	3	1	2	3	3	3	3	3
D	2	2	2	1	2	2	2	2	3
E	2	2	3	2	1	1	1	1	3
F	2	2	3	2	1	1	1	1	3
G	2	2	3	2	1	1	1	1	3
H	2	2	3	2	1	1	1	1	3
I	3	3	3	3	3	3	3	3	1

Figure 4.15 Combined Compatibility Matrix

Once the values are derived, we cluster the 1's (good compatibility measures) by employing the algorithm developed by Dr Kusiak and Chow to come up with appropriate module via CI software. Obtained Modules are

	A	B	C	D	E	F	G	H	I
A	1	1	3	2	2	2	2	2	3
B	1	1	3	2	2	2	2	2	3
C	3	3	1	2	3	3	3	3	3
D	2	2	2	1	2	2	2	2	3
E	2	2	3	2	1	1	1	1	3
F	2	2	3	2	1	1	1	1	3
G	2	2	3	2	1	1	1	1	3
H	2	2	3	2	1	1	1	1	3
I	3	3	3	3	3	3	3	3	1

Figure 4.16 Clusters obtained for the combined objective

The final matrix is obtained by mapping the modules from the decomposed matrix to the connection matrix which consists of connection data. Using this data and the precedence constraints as given in table 4.2, we try to obtain the modules for the combined objective case. Below is the connection matrix along with the clusters obtained from Figure 4.16.However this doesn't result in any changes in the clusters, hence obtaining the final modules for the combined objective as shown in figure 4.16

	A	B	C	D	E	F	G	H	I
A	*	*							
B	*	*	*	*	*				*
C		*	*	*					
D		*	*	*	*				
E		*		*	*	*	*	*	*
F					*	*			
G					*		*		
H					*			*	
I		*			*				*

Figure 4.17 Connection Matrix

Below is the final list of modules for the redesigned EnSeal Device Design with their Material and their Post life objective are given below

Table 4.10: Redesigned Endopath Xcel Trocar for the combined objective

Component	Material	Post Life Intent
A'. Obturator Housing Support Tube	ABS	Recycle
C. Shield Nose	POLY	Incinerate
D. Obturator Member	POLY	Reprocess

E'. Connector Control Knob Left Flang Right Flang	ABS	Reprocess
I. Cutting Blade	Stainless Steel	Reprocess

4.4.4 Connection Diagram and Feasible subassemblies

Now that the appropriate modules are obtained for the combined objective, the connection diagram of the product which gives the topological relations and constraints of the parts of the product is obtained as given below in figure 4.18

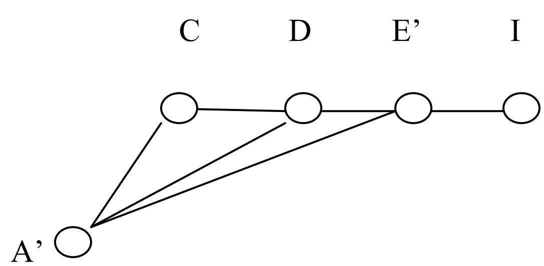

Figure 4.18 Trocar connection Diagram after Redesign

From the connection diagram the new A' is a module of components A, B and E' is a module of components from E-H.

Once the connection diagram is obtained, using reverse methodology, we try to obtain all the feasible subassemblies. The feasible subassemblies along with the precedence constraints are given below in figure 4.19

n=2	n=3	n=4	n=5
A'C +	A'CD+	A'CDE'+	A'CDE'I+
A'D A'D not C	A'CE' CE' not D	CDE'I+	
A'E' A'E' not C	A'DE' A'D not C		
CD+	CDE'+		
DE'+	DE'I+		
E'I+			

Figure 4.19 Geometrically Feasible Subassemblies of the Redesigned Product

4.4.5 Obtaining Transition Matrix

Now that the feasible subassemblies are obtained, we try to obtain the transition matrix for each type of material

a) For Retrieving ABS:

For the combined objective, from table 4.9, the parts made of ABS which needs to be recovered is given below

Table 4.11 Parts that needs to be recovered for Material Retrieval Objective

Component	Material
A'.Obturator Housing,Support Tube	ABS
E'.Connector,Control Knob,Left Flang,Right Flang	ABS

The objective here is to calculate the cost it incurs to recover this material from the device. From the table it is clear that we need to extract components A'E'. In order to do that we need to check figure 4.18 to see if these parts exists together as a subassembly or any other possible combinations with minimum number of disconnections.

From figure 4.18, we obtain only 1 possible sequence of disconnections in order to recover the ABS material. The AND/OR representation of the disassembly sequence is as given below

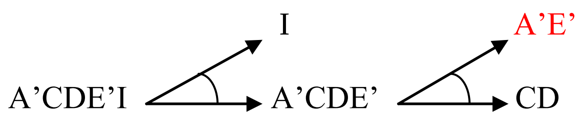

Figure 4.20 AND/OR representation of disassembly process

Below is the transition matrix for the disassembly sequence derived from the AND/OR diagram given in figure 4.20

	0	1	2
A’CDE’I	+1	-1	
A’CDE’		+1	-1
CD			+1
A’E’			+1
I		+1	

Figure 4.21 Transition Matrix to extract ABS from the Redesigned Product

b) To Retrieve Reprocessable material:

The objective here is to calculate cost it incurs to recover this material from the device. From the table 4.9, it is clear that we need to extract component D, E’ and I which have reprocessing as its post life objective. In order to do that we need to check table 4.19 to see if these parts exists together as a subassembly or any other possible combinations with minimum number of disconnections

From the table, we obtain only 1 possible sequence of disconnections in order to recover the ABS material. The AND/OR representation of the disassembly sequence is as given below

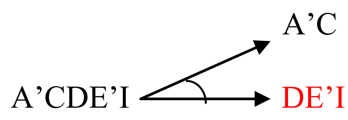

Figure 4.22 AND/OR representation of disassembly process to recover Reprocessable material

Below is the transition matrix that is obtained

	0	1
A’CDE’I	+1	-1
DE’I		+1
A’C		+1

Figure 4.23: Transition Matrix to extract material with reprocesses life intent for the redesigned product

4.4.6 Calculation of Resultant Profits

The same simplified cost vector will be implemented in this model as was implemented in the case before redesign. Costs are assigned as given below

Table 4.12: Cost vector being assigned

Operation	**Costs**
Single Disassembly	9.4
Parallel Disassembly/Module Disassembly	9.8

Along with the cost vector, revenue of 100 will be considered for desired modules and zero for the remaining

In this case

a) For Retrieving ABS,

Maximum Possible Profit = Possible Revenue from the desired Module -$\sum C_j X_j$ = 100 - (9.8+9.4) = 80.8

b) To Retrieving Reprocessable Material

Maximum Possible Profit = Possible Revenue from the desired Module -$\sum C_j X_j$ = 100 - (9.8) = 90.2

4.4.7 Calculating Modularity

We should be concerned with component disassembly in addition to material or post life compatibility when one employs a manual dismantling process. The less disassembly that has to be done to separate an assembly into material compatibility chunks, the better the design is for material retrieval.

Table 4.13: Redesigned Product Life Cycle Decomposition

Material Retrieval	Post Life	Material Retrieval & Postlife
Module 1: A,B Module 2: C Module 3: D Module 4:E,F,G,H Module 5: I	Module 1: A,B Module 2: C Module 3: D,E,F,G,H,I	Module 1: A,B Module 2: C Module 3: D Module 4:E,F,G,H Module 5: I
Number of Modules = 5	Number of Modules = 3	Number of Modules = 5
CI = 4/11	CI = 6/11	CI = 4/11

The actual arrangement and physical connectivity between components can be considered by including the Cluster Independence measure. CI for material recycling was determined by first counting the number of unique (symmetric matrix) shaded squares within the blocks along the diagonal from the

connection diagram in Figure 4.9, while ignoring diagonal entries. In this case, there are 4 intra-module connections ignoring the diagonal and redundant entries. As a general rule, CI penalizes architectures with many small modules, even though, at first glance, such architectures might be considered highly modular. Here the CI value for material recycling is smaller than for post life intent

Using the matrix format, this additional disassembly information can be shown along with the material compatibility. In Figure 4.17, the decomposed material compatibility matrix is augmented with physical connections between components shown by the shaded matrix elements. For each shaded element (i, j), it should be interpreted that the two components (i and j) are physically attached to one another. For example, in Figure 4.17, element (A, B) is shaded indicating that the Obturator housing (A) and Support Tube (B) are physically attached to one another via some fastening method. Note that this matrix is also square and symmetric. This method enables us to show which components need to be disassembled in order to separate the device into its material compatible modules

As can be seen from table 4.13, for material recover objective, it has 5 different modules for 9 different components. This means that the console must be separated into 5 groups to perform material retrieval on the whole product. A good rule of thumb is to reduce the number of different materials in a design in order to facilitate material retrieval

Table 4.14: Redesigned Product Life Cycle Objective Correspondence

Material Retrieval and Post Life

Obturator housing (A) and Support Tube (B) CR = 2:2 = 1.0 Shield Nose (C) CR=1:1= 1.0 Obturator Member (D) CR= 1:6 = 0.17 Connector (E), Left Flang (F),Right Flang (G),Control Knob (H) CR=4:6=0.66 Cutting Blade (I) CR=1:5 =0.16
Sum_CR= 3.0 CR_Overall= 0.6 CI = 4/11 Modularity= CR_overall * CI = 0.218

However improvement cannot be made simply by reducing the number of modules neglecting the actual physical connections between the components. One of the characteristics of modularity is to minimize the number of incidental interactions between components which can be used to analyze the

effort for separation. Just clustering a group of components together does not necessarily make the design better.

This arrangement and connectivity between components can be considered by including the Cluster Independence measure. CI for the combined objectives (Material retrieval & Postlife) is determined by counting the number of unique (symmetric matrix) * squares within the blocks along the diagonal in Figure 4.17 while ignoring diagonal entries. In this case, there are 4 shaded entries representing 4 intra-module connections. The total number of * entries is 11 ignoring diagonal and redundant entries. Hence, the CI measure is 11/28. The purpose of CI is that it penalizes architectures with many small modules even when such architectures might be considered highly modular.

Table 4.13 shows some of the modules that result from comparing objectives. For the modules listed with each module's Correspondence Ratio (CR) following a list of the module's components. For example, the first module contains only the component Obturator housing (A) and Support Tube (B) with CR=2:3=0.66.This CR was calculated by applying the CR equation to Material Retrieval Group 1 and Post life Group 1 from Table 4.8. In this case, $Vi(x) \cap Vj(x)$ = {Obtuarator housing (A), support tube (B)} which contains two components while $Vi(x) \cup Vj(x)$ contains 2 components too yielding a CR of 2:2 = 1.0. As can be seen from table 4.14, the two objectives for the redesigned device has an overall correspondence ratio of 0.6

The Final Measure which is used to evaluate the modularity is the modularity metric. It is a product of $CR_{overall}$ and CI measure for the combined objective redesigned product which is 0.218 as given in table 4.14. Since the theoretical best is equal to 1, we can infer that the results obtained here indicate poor modularity. This informs the designer can do other changes which can be made to increase the modularity measures by increasing the values of both $CR_{overall}$ and CI measure

4.4.8 Conclusion and Recommendations

Table 4.15 tabulates the profits that are obtained for all the possible cases. The profits under initial design refer to the profits that can be obtained for each objective. Under Redesign, for single objective, if the design of the architecture is designed with material retrieval alone, the profit that can be obtained is 80.8 and for post life objective it is 90.2. Refer Appendix I and Appendix II for profit calculations for material objective and post life objective, when considered individually for the redesigned product. If the device is redesigned with both the objectives in mind, then the profit obtained for material retrieval and post life is equal are 80.2 and 90.2 again. Usually the potential savings in the case of single objective is usually higher when compared to the combined objective after redesign, but not always as we are considering only a single objective. Considering only a single objective will help to simplify the product leading to lot less connections than the combined objective. However in this case, both the single objective and combined objective are leading to similar profits. Hence it is beneficial to redesign with the combined objective as it will easier for retrieving parts with respect to both the objectives. While comparing the profits, it can be observed that there is a consistent potential savings between 10-15% while comparing the initial design of the device to both the single and combined objective after redesign of the product. Hence redesign is recommended for this product

Also the values of modularity obtained for the case of redesigned product to be 0.436 which is still quite lower than the theoretical maximum of the 1 leaving a lot of room for improvement in the design. Looking at the factors which influence the modularity of the product, one can intuitively guess that by reducing the number of materials, by intelligently clustering compatible materials and by rethinking the post life intent for the various components of the design, we can potential decrease the number of connections and difference of material between the components

Table 4.15: Comparing the Profits obtained from devices between Initial Design and After Redesign

Standard Process		After Redesign			
Retrieve ABS	Retrieve Reprocessable Material	Retrieve ABS		Retrieve Reprocessable Material	
		Redesign according to Single Objective	Redesign according to Combined Objective	Redesign according to Single Objective	Redesign according to Combined Objective
71	80.8	80.8	80.8	90.2	90.2

This can lead to more profit and more material which can be recovered for reprocessing or for material retrieval. For example, the material for shield nose (C) and obturator member (D) can be changed from POLY to ABS material and the post life for shield nose can be changed to reprocess. These changes accomplishes 2 things

1) It eliminates the incineration category completely, helping to tighten the correspondence between the 2 objectives
2) It groups it with connector, control knob, left flang and right flang as they are of same material and have same post life intent

Chapter 5: Case Study 2

5.1 DESCRIPTION

For the second case study, we make use of another medical product manufactured by Ethicon Endo Surgery, which is part of the family of companies of Johnson & Johnson. The name of the device is EnSeal Laparoscopic Device

The EnSeal laproscopic device is a bipolar electrosurgical instrument primarily intended for use in open or laparoscopic, general and gynecological surgery to cut and seal vessels, and to cut, grasp and dissect tissue during surgery

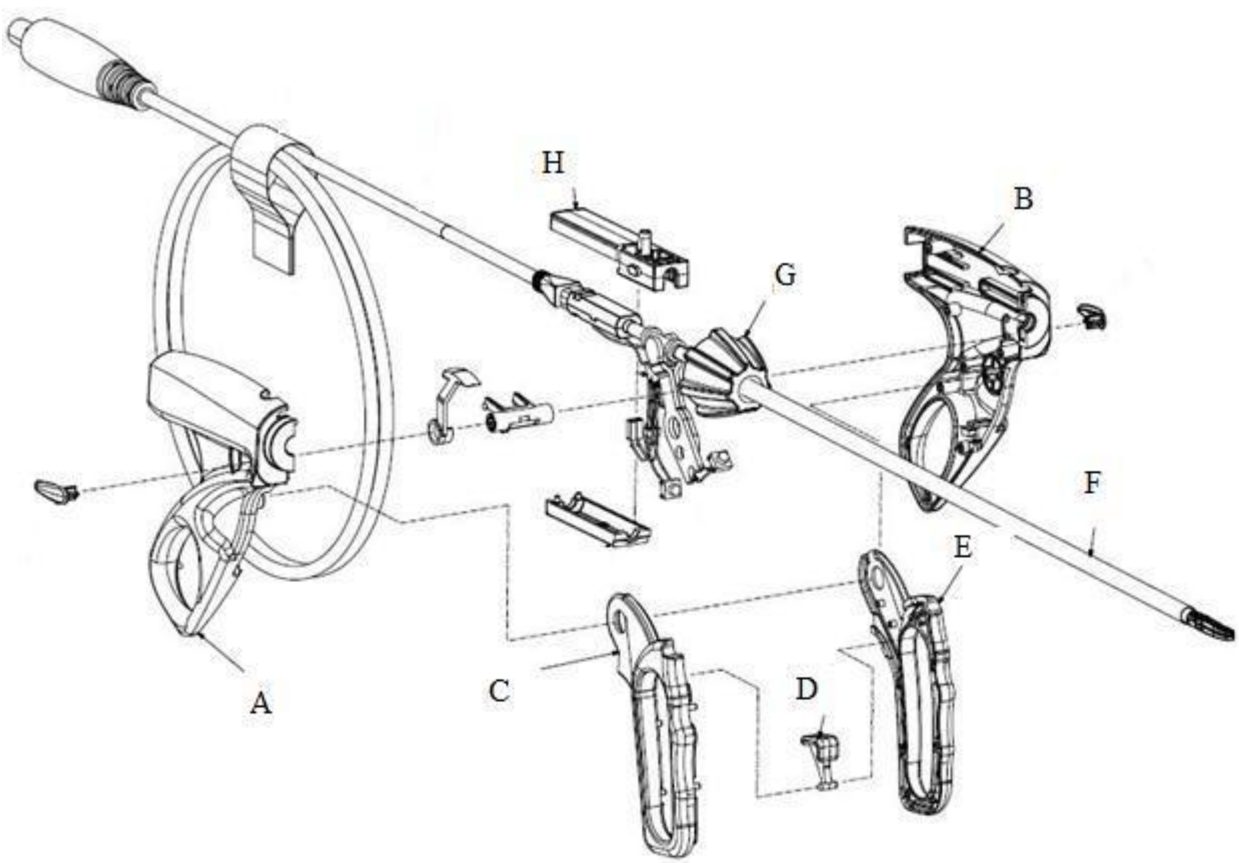

Figure 5.1: Exploited View of the Laparoscopic Device

This device can be used for vessel ligation (cutting and sealing), tissue grasping and dissection. The devices can be used on vessels up to (and including) 7 mm and bundles as large as will fit in the jaws of the instruments. The device consists of many major and minor components.

For this study purpose, we will consider parts which are architecturally and revenue wise critical. This will also lead to less number of parts to consider which will further simplify the problem

The components which we considered are given in table 5.1 along with their most commonly used material and post life intent. The device has an ergonomic handle for better grip with the ability to rotate the jaws single handed. The length and diameter of the shaft varies depending on each instrument and the surgery it is intended for. The Shaft is the one that is introduced into the patient's body in order to carry out the surgery. The instrument ends with the jaws that are the ones that transmit the energy in order to seal the vessels; this section also includes the I-blade, which the part the cuts the vessels once they have been sealed. The instrument also has the ability to only cut without sealing, or to only grasp tissue without cutting or sealing. The materials utilized in the components of the trocar system generally include materials such as either Acrylonitrile butadiene styrene (ABS) or polycarbonate resin thermoplastic (POLY) for handle and lever section and stainless steel for components that are required to cut the tissue

Table 5.1: EnSeal Device Design with their Material and their Post life objective

Component	Material	Post Life Intent
A.Handle,Right Hand Activation	ABS	Recycle
B.Handle,Left Hand Activation	ABS	Recycle
C.Lever,Right Hand Activation	POLY	Reprocess
D.Trigger,Hand Activation	POLY	Reprocess
E.Lever,Left Hand Activation	POLY	Reprocess
F.Shaft Jaw ASM bonded 3mm 35cm	Stainless Steel	Incinerate
G.Rotator,Hand Activation	POLY	Incinerate
H.Housing Body,Hand Activation	ABS	Recycle

5.2 Identification of Objectives

The 2 main objectives we are considering in this case are

a) Material Retrieval and

b) Good Post Life Intent

In order to apply the methodology, below is the exploited view of Enseal Laproscopic device. In table 5.1, the parts are listed along with what kind of material it is made of and its post life destination (recycle, reprocess or incineration)

In this disassembly-to-order problem, it consists of 2 major steps in order to compare them

1. For the Initial Design, costs will be calculated which will be required to recover ABS material (material retrieval objective) and parts meant for RECYCLING (post life objective) for the initial design

2. Once the values are calculated, the product will be redesigned according to material retrieval and post life objectives and costs will be calculated along with modularity measures which will serve as an index of how good the redesign effort has been in relation to the objectives and if there is any more room for improvement

5.3 BEFORE REDESIGN

5.2.1 Connection Diagram and Feasible Subassemblies

The first step is to obtain the connection diagram of the product for the initial design which will give the topological relations and constraints of the parts of the product. For figure 4.1, below is the connection diagram that is obtained.

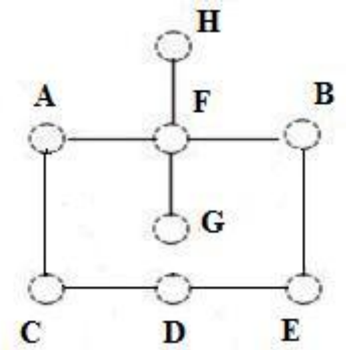

Figure 5.2 Connection Diagram for the Initial Design

Once the connection diagram is obtained, using reverse methodology, we try to obtain all the feasible subassemblies. Below is the table which contains all the possible subassemblies

Table 5.2: Geometrically Feasible Subassemblies for the Initial Design

n=2	n=3	n=4	n=5	n=6	n=7
AC+	ACF+	ACDF+	ABCDF+	ABCDFG+	ABCDFGH+
AF+	ACD+	ABCF+	ACDFG+	ABCDFH+	ABCDEFG+
BE+	ABF+	ACFG+	ACDFH+	ABCDEF+	ABCDEFH+
BF+	AFG+	ACFH+	ACDEF+	ACDFGH+	ACDEFGH+
CE CE not D	AFH+	ACDE+	ACFGH+	ACDEFG+	
CD+	BEF+	ABFG+	ABCFG+	ACDEFH+	
DE+	BDE+	ABFH+	ABCDE AB not F	ABCFGH+	
FG+	BFG+	ABEF+	ABFGH+	ABCEFG CE not D	
FH+	BFH+	AFGH+	ABEFG+	ABEFGH+	
	CDE+	BDEF+	ABEFH+		
	FGH+	BEFG+	BEFGH+		
		BEFH+	BCDEF+		
		BCDE+			
		BFGH+			

5.2.2 Obtaining Transition Matrix for each objective

To obtain the transition matrix, let us consider one objective at a time

a) For Recovering ABS

From Table 5.1, the parts made of ABS which needs to be recovered are re-listed below

Table 5.3: Parts made of ABS which needs to be recovered

Component	Material	Post Life Intent
A.Handle,Right Hand Activation	ABS	Recycle
B.Handle,Left Hand Activation	ABS	Recycle
H.Housing Body,Hand Activation	ABS	Recycle

The objective here is to calculate the cost it incurs to recover this material from the device. From the table it is clear that we need to extract components A, B and H. In order to do that we need to check table 5.2 in order to find out the sequence which will help us to recover these parts. Starting from the complete product, we map out the sequences which will recover the required parts which has least number of disconnections. From table 5.2, only 1 sequence can be mapped which recovers the required material.

Below is the AND/OR representation of the disassembly process

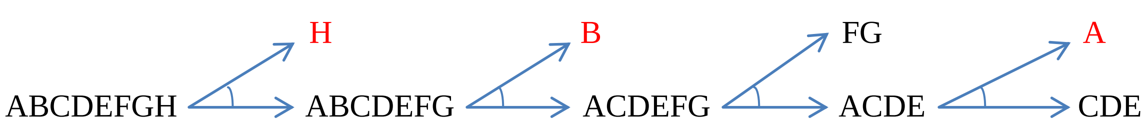

Figure 5.3: AND/OR representation of the disassembly process to recover ABS

Table 5.4 is the transition matrix obtained for the sequence required to recover the parts made of ABS material. As given in table 5.4, it requires 4 disconnections to obtain our required parts which are A, B and H

Table 5.4: Transition Matrix to recover ABS

	0	1	2	3	4
ABCDEFGH	+1	-1			
ABCDEFG		+1	-1		
ACDEFG			+1	-1	
ACDE				+1	-1
CDE					+1
FG				+1	
A					+1
B			+1		
H		+1			

From the end product, we start by removing component H. From here we have limited number of ways we can proceed forward to recover the remaining parts. After removing B, we are left with the subassembly ACDEFG. It is observed that FG and CDE can exist as subassemblies from the table. Hence by parallel disassembly we remove FG after which A is recovered by disassembling A and CDE

b) To recover Reprocessable material:

From figure 5.1 and table 5.1, the parts made of Reprocessable material which needs to be recovered are given below

Table 5.5: Parts made of Reprocessable material as their Post Life Objective

Component	Material	Post Life Intent
C.Lever,Right Hand Activation	POLY	Reprocess
D.Trigger,Hand Activation	POLY	Reprocess
E.Lever,Left Hand Activation	POLY	Reprocess

From table 5.1, it can be intuitively observed that to recover parts from C, D and E with minimum number of disconnections, we start off by disconnecting E to obtain ABCDFGH. Sequentially the next part ideally to be removed is part D and later from subassembly ABFGH, we recover part C. Below is the AND/OR representation of the disassembly process

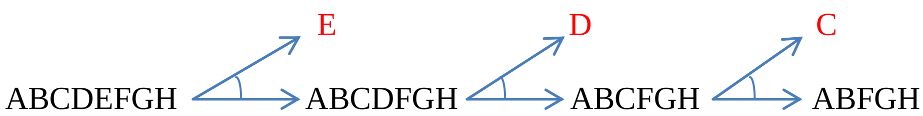

Figure 5.4: AND/OR representation of the disassembly process to recover Reprocessable material

Table 5.6 illustrates the transition matrix that is obtained from the disassembly process to recover Reprocessable parts from the medical device

Table 5.6: Transition Matrix to obtain Reprocessable parts

	0	1	2	3
ABCDEFGH	+1	-1		
ABCDFGH		+1	-1	
ABCFGH			+1	-1
ABFGH				+1
C				+1
D			+1	
E		+1		

5.2.3 Calculation of Resultant Profits

A simplified cost vector is introduced in the model, similar to the one used in the previous case. Costs are assigned as given below

Table 5.7: Cost vectors being assigned

Operation	Costs
Single Disassembly	9.4
Parallel Disassembly/Module Disassembly	9.8

As shown in the table 5.7, apart from the removal of single parts, parallel disassembly has to be considered too. For simplicity purposes, we assign 9.4 for removing each single part and 9.8 for each parallel disassembly.

Along with the cost vector, we also need to assign the revenue vector and calculations will be carried out by considered a revenue of 100 for set of all desired modules and zero for the remaining

a) For Recovering ABS,

The transition matrix table 5.4 is the sequence which helps to recover the ABS material. By applying the formula to the transition matrix, we obtain

Possible Profit from the desired Module $-\sum C_jX_j$ = 100 - (9.4* 3 + 9.8) = 62

b) To Recover Reprocessable Material

The transition matrix 4.6 is the only feasible sequence which helps to recover the ABS material. By applying the formula to the transition matrix, we obtain

Possible Profit from the desired Module $-\sum C_jX_j$ = 100 – (9.4*3) = 71.8

Hence the maximum possible profit that can be obtained before redesign for the 2 objectives that we have considered is given below

Table 5.8: Maximum Profit that can be obtained for Initial Design

Objective	Profit
Recovering ABS	62
Recover Reprocessable Material	71.8

5.3 REDESIGNING THE DEVICE

The information given in Table 5.1 will be used to determine the modules (sets of components that share a common characteristic) that exist for different objectives. For instance, for material retrieval objective, the ideal design would have all the components made of a single material since the product would not need disassembly and could just be reprocessed as it is.

5.3.1 Material Retrieval

Figure 5.5 is the material compatibility matrix that is derived from table 5.1 for material Retrieval objective. Once the values are derived, the objective is to cluster the 1's (good compatibility measures) by employing the algorithm developed by Dr Kusiak and Chow to come up with appropriate module via CI software developed at University of Texas at El Paso. The objective here is to cluster all the 1's while all other compatibility values are neglected. The output of the software is given in figure 5.6.The results from Figure 5.6 is used to come up with clusters as given in Figure 5.7. Once the clusters are obtained, the connection between each component is examined and they need to be divided into further clusters if there doesn't exist a connection between them or if there is any precedence constraints. The connection matrix is given in figure 5.8.Examining the connections only within the

clusters, it can be observed that there is the components which are physically connected to each other form a matrix which is square and symmetric. For example, examine column A and B, there exist no square matrix within the cluster region. However when examing column C and D, they form a square and symmetric matrix. Similarly column C and E, if placed side by side, forms a square and symmetric matrix. Also the resultant clusters comply with the precedence constraint CE not D as given in table 5.2.Using that information, the clusters are further divided into the final clusters shown in figure 5.9.This scheme is used to show which components needs to be disassembled from which others in order to separate the device into its material compatible components. The result in figure 5.9 gives the final modules for material retrieval objective alone.

	A	B	C	D	E	F	G	H
A	1	1	2	2	2	3	2	1
B	1	1	2	2	2	3	2	1
C	2	2	1	1	1	3	1	2
D	2	2	1	1	1	3	1	2
E	2	2	1	1	1	3	1	2
F	3	3	3	3	3	1	3	3
G	2	2	1	1	1	3	1	2
H	1	1	2	2	2	3	2	1

Figure 5.5: Material Compatibility Matrix

	A1	A2	A8	A3	A4	A5	A7	A6
C1	X	X	X					
C2	X	X	X					
C8	X	X	X					
C3				X	X	X	X	
C4				X	X	X	X	
C5				X	X	X	X	
C7				X	X	X	X	
C6								X

Figure 5.6 Clusters obtained by using CI software

	A	B	H	C	D	E	G	F
A	1	1	1	2	2	2	3	3
B	1	1	1	2	2	2	2	3
H	1	1	1	2	2	2	2	3
C	2	2	2	1	1	1	1	3
D	2	2	2	1	1	1	1	3
E	2	2	2	1	1	1	1	3
G	2	2	2	1	1	1	1	3
F	3	3	3	3	3	3	3	1

Figure 5.7 Mapping the results from CI software onto the material compatibility matrix

	A	B	H	C	D	E	G	F
A	*			*				*
B		*				*		*
H			*					*
C				*	*	*		
D				*	*	*		
E		*		*	*	*		
G							*	*
F	*	*	*				*	*

Figure 5.8 Connection Matrix

	A	B	H	C	D	E	G	F
A	1	1	1	2	2	2	3	3
B	1	1	1	2	2	2	2	3
H	1	1	1	2	2	2	2	3
C	2	2	2	1	1	1	1	3
D	2	2	2	1	1	1	1	3
E	2	2	2	1	1	1	1	3
G	2	2	2	1	1	1	1	3
F	3	3	3	3	3	3	3	1

Figure 5.9 Modules obtained for Material Retrieval Objective

5.3.2 For Post Life Objective

Figure 5.10 is the Post Life objective compatibility matrix that is derived from table 5.1. Once the values are derived, the objective is to cluster the 1's (good compatibility measures) by employing the algorithm developed by Dr Kusiak and Chow to come up with appropriate module via CI software developed at University of Texas at El Paso. The output of the software is given in figure 5.11.The results from Figure 5.11 is used to come up with clusters as given in Figure 5.12. Once the clusters are obtained, the connections between each component is examined and the clusters need to divided into further clusters if there doesn't exist a connection between any 2 components present in a cluster. The connection matrix is given in figure 5.13.Examining the connections only within the clusters, when examining any two columns together, it can be observed that there are components which are physically connected to each other forming a matrix which is square and symmetric implying that they are connected to each other. Using that information, the clusters are further divided into the final clusters shown in figure 5.14.This scheme is used to show which components needs to be disassembled from which others in order to separate the device into its material compatible components. The result in figure 5.14 gives the final modules for post life objective

	A	B	C	D	E	F	G	H
A	1	1	2	2	2	3	3	1
B	1	1	2	2	2	3	3	1
C	2	2	1	1	1	3	3	2
D	2	2	1	1	1	3	3	2
E	2	2	1	1	1	3	3	2
F	3	3	3	3	3	1	1	2
G	3	3	3	3	3	1	1	3
H	1	1	2	2	2	2	3	1

Figure 5.10 Compatibility Matrix for Post Life objective

	A1	A2	A8	A3	A4	A5	A6	A7
C1	X	X	X					
C2	X	X	X					
C8	X	X	X					
C3				X	X	X		
C4				X	X	X		
C5				X	X	X		
C6							X	X
C7							X	X

Figure 5.11 Clusters obtained after matrix decomposition using the CI software

	A	B	H	C	D	E	F	G
A	1	1	1	2	2	2	3	3
B	1	1	1	2	2	2	3	3
H	1	1	1	2	2	2	2	3
C	2	2	2	1	1	1	3	3
D	2	2	2	1	1	1	3	3
E	2	2	2	1	1	1	3	3
F	3	3	3	3	3	3	1	1
G	3	3	3	3	3	3	1	1

Figure 5.12 Clusters obtained after matrix decomposition

	A	B	H	C	D	E	G	F
A	*			*				*
B		*				*		*
H			*					*
C				*	*	*		
D				*	*	*		
E		*		*	*	*		
G							*	*
F	*	*	*				*	*

Figure 5.13 The connection matrix

	A	B	H	C	D	E	F	G
A	1	1	1	2	2	2	3	3
B	1	1	1	2	2	2	3	3
H	1	1	1	2	2	2	2	3
C	2	2	2	1	1	1	3	3
D	2	2	2	1	1	1	3	3
E	2	2	2	1	1	1	3	3
F	3	3	2	3	3	3	1	1
G	3	3	3	3	3	3	3	1

Figure 5.14 Modules obtained for Post Life Objective

5.3.3 For Combined Objectives

After it has been determined how the device can be redesigned into appropriate modules for each objective alone, now the objectives will be combined in order to redesign the product complying to both the objectives at the same time.

In this case similar procedure will be followed to obtain the desired modules. However we obtain the compatibility matrix by mapping the compatibility of each part with regards to both the objectives as given in table 5.1 with every other part on a scale of 1-3 hence obtaining the final compatibility matrix. These values are obtained based on the lowest value (1 is highest and 3 is lowest) while comparing each part with every other part based both on material compatibility and post life objective data together. For example, while comparing the compatibility based on material and post life objective between handle (right hand activation) and rotator (hand activation), the values are 2 and 3 respectively. Since the value 3 is the lowest, in the combined objective matrix, we substitute 3 for the compatibility value between these two parts.

The final matrix is given in figure 5.15 as given below

	A	B	C	D	E	F	G	H
A	1	1	2	2	2	3	3	2
B	1	1	2	2	2	3	3	2
C	2	2	1	1	1	3	3	2
D	2	2	1	1	1	3	3	2
E	2	2	1	1	1	3	3	2
F	3	3	3	3	3	1	3	3
G	3	3	3	3	3	3	1	3
H	2	2	2	2	2	3	3	1

Figure 5.15 Compatibility Matrix for combined objective

Once the values are derived, we cluster the 1's (good compatibility measures) by employing the algorithm developed by Dr Kusiak and Chow to come up with appropriate module via CI software. The output of the software is given in figure 5.16.The results from Figure 5.16 is used to come up with clusters as given in Figure 5.17. Once the clusters are obtained, the connections between each component is examined and the clusters need to divided into further clusters if there doesn't exist a connection between any 2 components present in a cluster. The connection matrix is given in figure 5.18.Examining the connections only within the clusters, it can be observed that there are components which are physically connected to each other forming a matrix which is square and symmetric implying that they are connected each other. Using that information, the clusters are further divided into the final clusters shown in figure 5.19.This scheme is used to show which components needs to be disassembled from which others in order to separate the device into its combined objective compatible components. The results in figure 5.19 give the final modules for the combined objective

	A1	A2	A3	A4	A5	A6	A7	A8
C1	X	X						
C2	X	X						
C3			X	X	X			
C4			X	X	X			
C5			X	X	X			
C6						X		
C7							X	
C8								X

Figure 5.16 Screenshot of the clusters obtained using CI software

	A	B	C	D	E	F	G	H
A	1	1	2	2	2	3	3	2
B	1	1	2	2	2	3	3	2
C	2	2	1	1	1	3	3	2
D	2	2	1	1	1	3	3	2
E	2	2	1	1	1	3	3	2
F	3	3	3	3	3	1	3	3
G	3	3	3	3	3	3	1	3
H	2	2	2	2	2	3	3	1

Figure 5.17 Decomposed Matrix

	A	B	C	D	E	F	G	H
A	*		*			*		
B		*			*	*		
C			*	*	*			
D			*	*	*			
E		*	*	*	*			
F	*	*				*	*	*
G						*	*	
H						*		*

Figure 5.18 The Connection Diagram

	A	B	C	D	E	F	G	H
A	1	1	2	2	2	3	3	2
B	1	1	2	2	2	3	3	2
C	2	2	1	1	1	3	3	2
D	2	2	1	1	1	3	3	2
E	2	2	1	1	1	3	3	2
F	3	3	3	3	3	1	3	3
G	3	3	3	3	3	3	1	3
H	2	2	2	2	2	3	3	1

Figure 5.19 Final Modules for Combined Objective

Below is the final list of modules for the redesigned EnSeal Device Design with their Material and their Post life objective are given below

Table 5.9: Redesigned Enseal Device Design for the combined objective

Component	Material	Post Life Intent
A.Handle,Right Hand Activation	ABS	Recycle
B.Handle,Left Hand Activation	ABS	Recycle
C'. Lever, Right Hand Activation Trigger, Hand Activation Lever, Left Hand Activation	POLY	Reprocess
F.Shaft Jaw ASM bonded 3mm 35cm	Stainless Steel	Incinerate
G.Rotator,Hand Activation	POLY	Incinerate
H.Housing Body, Hand Activation	ABS	Recycle

5.3.3.1 Connection Diagram and Feasible subassemblies

Now that the final modules are obtained, the feasible subassembly has to be determined. The connection diagram of the product which gives the topological relations and constraints of the parts of the product is obtained as given below in figure 5.18

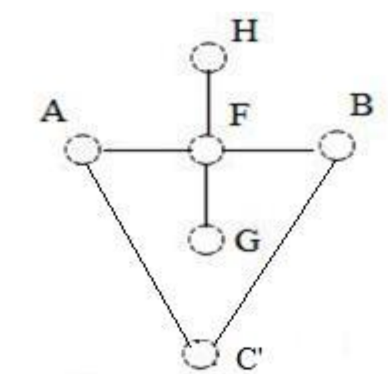

Figure 5.20 Connection Diagram for the combined objective

From the connection diagram C' denotes a module which consists of combination of old components {C, D, E}.Once the connection diagram is obtained, using reverse methodology, we try to obtain all the feasible subassemblies. The feasible subassemblies along with the precedence constraints are given below in table 5.10

Table 5.10 Feasible Subassemblies for Combined Objective

n=2	n=3	n=4	n=5
AF+	AC'F+	ABC'F+	ABC'FH+
AC'+	ABF+	AC'FH+	ABC'FG+
BF+	AFH+	AC'FG+	AC'FGH+
BC'+	AFG+	ABFH+	ABFGH+
FH+	ABC' AB not F	ABFG+	BC'FGH+
FG+	BC'F+	AFGH+	
	BFH+	BC'FH+	
	BFG+	BC'FG+	

5.3.3.2 Transition Matrix for Each Objective

Now that the feasible subassemblies are obtained, we try to obtain the transition matrix for each objective for the redesigned product

a) To recover ABS material:

The objective here is to calculate the cost it incurs to recover ABS material from the redesigned device. From the table 5.9 it is clear that we need to extract components A, B, H from other components of the redesigned device as shown in figure 5.20. In order to do that we need to check table 5.10 to see if

these parts exists together as a subassembly or any other possible combinations with minimum number of disconnections

Table 5.11 List of ABS material that needs to be recovered for combined objective

Component	Material	Post Life Intent
A.Handle,Right Hand Activation	ABS	Recycle
B.Handle,Left Hand Activation	ABS	Recycle
H.Housing Body,Hand Activation	ABS	Recycle

From table 5.10, we look for all the possible sequences by which these parts can be recovered. Below is the AND/OR diagram that is obtained for recovering ABS material

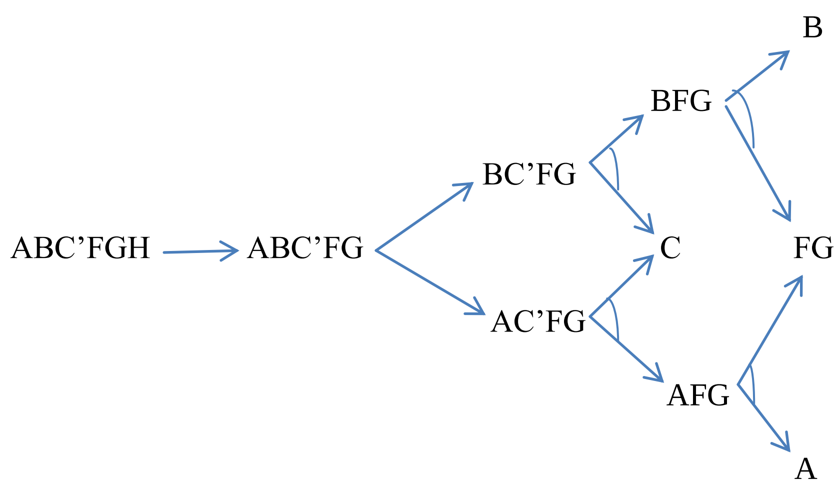

Figure 5.21 AND/OR disassembly representation for recovering ABS for combined objective

Since according to our cost calculations, we are looking for a sequence which has the least number of disconnections, we can select any one of the above sequences. Hence the transition matrix is as given below

Table 5.12: Transition Matrix obtained to recover ABS for the combined objective

	0	1	2	3	4
ABC’FGH	+1	-1			
ABC’FG		+1	-1		
BC’FG			+1	-1	
BFG				+1	-1
FG					+1
A			+1		
B					+1
C’				+1	
H		+1			

b) To Recover Reprocessable Material

From Table 5.11,the module made of ABS for the redesigned product which needs to be recovered in the redesigned product is module C’ where C’ = {Handle, Right hand Activation; Handle, Left hand Activation; Housing Body, Hand Activation}.The objective here is to figure out the sequence for recovering C’ in minimum number of disconnections. From table 5.10, there is only 1 possible sequence which is

ABC’FGH ➔ ABFGH + C’

Below is the AND/OR diagram that is obtained for recovering reprocessable material from the device.

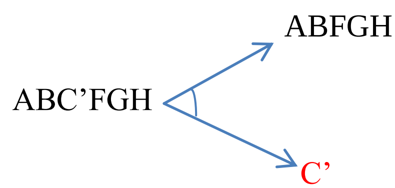

Figure 5.22: AND/OR representation of the disassembly for recovering Reprocessable material

Hence the transition matrix for the above sequence is as given below

Table 5.13 Transition Matrix obtained for recovering Reprocessable material for combined objective

	0	1
ABC'FGH	+1	-1
ABFGH		+1
C'		+1

5.3.5 Calculation of Resultant Profits

The simplified cost vector will be implemented in this model as was implemented in the previous case study. Costs are assigned as given below

Table 5.14: Cost vector being assigned

Operation	**Costs**
Single Disassembly	9.4
Parallel Disassembly/Module Disassembly	9.8

Along with the cost vector, revenue of 100 will be considered for all desired modules and zero for the remaining

In this case

a) For Retrieve ABS,

Possible Profit = Possible Revenue from the desired Module $-\sum C_jX_j$ = 100-(9.4*3 +9.8) = 62

b) To Retrieve Reprocessable Material

Possible Profit = Possible Revenue from the desired Module -$\sum C_jX_j$ = 100 – 9.8 = 90.2

5.3.6 Calculating Modularity

Table 5.15: Redesigned Product Life Cycle Decomposition

Material Retrieval	Post Life	Material Retrieval & Postlife
Module 1: A Module 2:B Group 3: C,D,E Group 4: F Group 5:G Group 6: H	Module 1: A Module 2:B Module 3:C,D,E Module 4: F Module 5: G Module 6:H	Module 1: A Module 2:B Module 3:C,D,E Module 4: F Module 5: G Module 6:H
Number of Modules = 6	Number of Modules = 6	Number of Modules = 6
CI = 4/10	CI = 4/10	CI = 4/10

In this case, the architectures of Material Retrieval and Post life complies completely with the architecture of the combined objective giving us CR_overall=1 for the combined objective with CI of 4/10.Hence modularity for the combined objective equals 0.4. Since the theoretical best is equal to 1, we can conclude that the results obtained here indicates poor modularity

5.3.7 Conclusion and Recommendations

The obtained modularity value for the combined objective equals 0.4 which is less than the theoretical best of 1.This informs the designer can recommend other changes which can be made to increase the modularity measures by increasing the values of CI measure in order to bring the value of modularity closer to 1.In other words, we can try to decrease the number of connections between

different types of modules by using ABS material for Lever (right hand activation),Lever (Left hand Activation) and Trigger similar to Handle (right hand activation) and Handle (Left Hand Activation) and changing the post life intent to recycling. These changes provide one strong advantage. It rounds out the reprocess category helping it to group with the Handle (Left and right hand activation) as they are of the same material and have the same post life intent

Table 5.16: Profits obtained for Initial and Redesigned EnSeal Laproscopic Device

Standard Process		After Redesign			
Retrieve ABS	Retrieve Reprocessable Material	Retrieve ABS		Retrieve Reprocessable Material	
		Redesign according to Single Objective	Redesign according to Combined Objective	Redesign according to Single Objective	Redesign according to Combined Objective
62	71.8	62	62	90.2	90.2

Table 4.9 tabulates the profits that are obtained for all the possible cases. Since the architecture design for single objective is similar to combined objective, the profits from the redesigned device for material retrieval and post life objectives when considered individually is similar to the profit that can be obtained for the combined objective for the redesigned device

Chapter 6: Future Work

The framework which is developed is ideal for devices which are not too complex and few life cycle objectives. However with increase in complexity, further research and work will be required in order to improve upon the model in order to make it more accurate and less time consuming.

1. The disassembly process is done without considering the technical constraints of the product. Further work needs to be done to see if the technical constraints can affect the redesign effort

2. If it is required, more life cycle objectives can be considered at the expense of more time consumption and complexity

3. While calculating the disassembly sequences, the list of selective disassembly sequences are calculated manually from the list of feasible subassemblies that are obtained after implementing the reverse methodology. This approach is satisfactory as long as the device is not too complex. For complex devices, one of the approaches is to decrease the complexity of the problem by considering subassemblies or in terms of modules. Another approach is to conduct more research in selective disassembling taking into consideration the search must be conducted to identify total number of ways different parts can be considered together as subassembly unlike the present research in selective disassembly which consider only a set of parts that needs to be recovered and the required sequences are obtained

4. It must be noted that for cost assumptions which were made, the cost for each disconnection doesn't vary too much which is usually the case. These assumptions were made using a simple model wherein the disconnection is either sequential disassembly or a parallel disassemble or if it is module disconnection. However in the real world some disconnections incur more cost than others. A more sophisticated model can be incorporated in order to take into account those factors and calculate costs accordingly

5. This study is calculated based on revenue alone. However more research can be conducted in order to incorporate time as another factor and include factors like time for tool changeover required for disassembling the components
6. Apart from the 2 objectives (Material and Post life), more objectives can also be considered. For example, service objective can also be added for which the compatibility values are based on the ease of retrieving the part for repair and put it back again to increase the life of the product

References

1. Tietjen, L., Bossemeyer, D., & McIntosh, N. (2003). Infection Prevention : Guidelines for Healthcare Facilities with Limited Resources. Jhpiego,1-13
2. L, Girion and Alonso-Zaldivar R. "Steep rise projected for health spending." Los Angeles times 22 Feb. 2006: 8. Print
3. A, Klein. "Reused devices attract entrepreneurs scrutiny." Washington Post 12 Dec. 2005: 3-4. Print
4. Vukelich (2009). Reprocessing "Single use" medical devices : A sustainable Solution. Health Development Care Magazine, 28-35
5. Sloan, T. (2006). Safety-cost trade-offs in medical device reuse: a Markov decision process model. Springer Science,1-2
6. Kadamus, C. (2008, 1). Medical Design | Home. Sustainable design for medical devices | Prototyping content from Medical Design. Retrieved December 10, 2012, from http://medicaldesign.com/prototyping/sustainable-design-medical-devices
7. Leonard, P. (2011). Carbon Design Group | Full-Service Product Design & Development. Sustainability in Medical Device Design: Turning Challenge into Opportunity | News | Carbon Design Group. Retrieved 2012, from http://www.carbondesign.com/sustainability-in-medical-device-design-turning-challenge-into-opportunity
8. James, F. (1994). Framework for life cycle Inventory. A Technical Framework for Life-cycle Assessment,Washington DC: SETaC Foundation, 9-12
9. Consoli, F., Boustead, I., Fava, J., & Franklin, W. (1993). Guidelines for Life-Cycle Assessment: A Code of Practice. SETAC : 2-5
10. 14040, I.D.(1997), Environmental Management-Life Cycle Assessment-Part 1: Principles and Framework
11. ISO/TC 207/SC 5/ N 112, I.D (1998), Environmental Management - Life Cycle Assessment - Part 3. Life Cycle Impact Assessment, Committee draft
12. ISO/TC 207/SC 5/ N 112, I.D (1998), Environmental Management - Life Cycle Assessment - Part 4. Life Cycle Interpretation, Voting draft
13. ISO/TC 207/SC 5/WG 2 N 112, I.D (1997), Environmental Management-Life Cycle Assessment-Part 2. Goal and Scope Definition and Life Cycle Inventory Analysis,Voting Draft
14. R, H. (2001). Life Cycle Assessment: An Operational Guide to ISO standards . Retrieved from http://media.leidenuniv.nl/legacy/new-dutch-lca-guide-part-1.pdf
15. H. Hallay, R.P (1992), in OÈ ko-Controlling Umweltschutz in mittelsta Èndischen Unternehmen, Campus, Frankfurt,122-145
16. S.H. Kalisvaart, J.A.M.R (1994), The Met-points Method: A new single figure environmental performance indicator, in H.A.,Udo de Haes, A.A. Jensen, W. KloÈpffer, L.-G. Lindfords, (Eds.),Integrating Impact Assessment into LCA, SETAC : Europe,Brussels, 3-22
17. Jolliet, O (1996), Impact Assessment of Human and Eco-toxicity in Life Cycle Assessment. In: H.A. Udo de Haes, (Ed.), in Towards a Methodology for Life Cycle Impact Assessment, SETAC-Europe: Brussels, 4-9
18. Habersatter, K (1991), OÈ ekobilanz von Packstoffen Stand 1990; Schriftenreiche Umwelt 132, Bundesamt fuÈr Umwelt, Wald und Landschaft,Bern, 9-12
19. Goedkoop, M (1995), The Eco-indicator 95. 1995: Netherlands Agency of Energy and Environment (NoVEM), Amersfoort, 10-11

20. S. Ahbe, A.B., R. MuÈ ller-Wenk (1990) , in Methodik fuÈ rOÈ kobilanzen auf der Basis oÈkologischer Optimierung. Schriftenreihe Umwelt Nr. 133, Bundesamt fuÈ r Umwelt, Wald und Landschaft (BUWAL) : Bern, 81-109
21. Saur, K. (1997). Life Cycle Interpretation - A Brand New Perspective. International Journal LCA, 8-10
22. Tahara, K., Kojima, T., & Inaba, A. (1997). Evaluation of CO2 payback time of power plants by LCA. Energy Conversion and Management, 8-16
23. Pitipong Veerakamolmal, S.G., Design for Disassembly, Reuse, and Recycling, in Environmentally responsible engineering. 2000, Northeastern University: Boston, 69-82.
24. Chiodo, D.J., Design for Disassembly Guidelines. Active Disassembly Research, 2005. **2**(1): 29-37
25. Fred,L. (2005). Industrial Ecology. Disassembly modeling for Assembly,Maintenance,Reuse,and Recycling (Second ed., pp. 23-3). CRC Press
26. Kara, S., Pornprasitpol, P., Kaebernick, H., A selective disassembly methodology for end-of-life products, Emerald Group Publishing Limited, 124-134
27. Pamela, M. (1993). The Garbage Primer (pp. 23-5). Lyons & Burford
28. Agency, U.S.E.P. Comprehensive Procurement Guidelines. Wastes - Resource Conservation - Comprehensive Procurement Guidelines 2012
29. Gershenson, J.K., Prasad, G.J., & Allamneni, S. (1999). Modular Product Design: A Life-cycle View. Journal of Integrated Design and Process Science, 3(4), 1-3
30. Newcomb, P., Bras, B., & Rosen, D. (1996). Implications of Modularity on Product Design for the life cycle. The 1996 ASME Design Engineering Technical Conferences and Computers in Engineering Conference, 1-3
31. Cabigiosua, A., & Camuffo, A. (2013). Modularity, interfaces definition and the integration of external sources of innovation in the automotive industry. Research Policy, 42(3), 6-10
32. Denning, S. (2012, 01). Information for the World's Business Leaders - Forbes.com. Transformational Leadership In Agile Manufacturing: Wikispeed - Forbes. Retrieved February 20, 2013, from http://www.forbes.com/sites/stevedenning/2012/08/01/transformational-leadership-in-agile-manufacturing-wikispeed/
33. Alfred, L. (2005). Geometric constraints and Precedence Relationships. Disassembly modeling for Assembly,Maintenance,Reuse and Recycling (2 ed., pp. 167-22). CRC Press
34. Newcomb, Patrick, Bert Bras and David Rosen. "Implications of Modularity on Product Design for the life cycle." The 1996 ASME Design Engineering Technical Conferences and Computers in Engineering Conference. (1996): 2-3
35. Alfred, L. (2005). The Disassembly Process. Disassembly modeling for Assembly,Maintenance,Reuse and Recycling (2 ed., pp. 73-11). CRC Press
36. Lambert, A.J.D.F., Optimizing disassembly processes subjected to sequence-dependent cost. Computers and Operations Research, 2005 : 536-551

Appendix I – Profit calculations for Material retrieval objective

	A	B	E	F	G	H	C	D	I
A	1	1	1	1	1	1	2	2	3
B	1	1	1	1	1	1	2	2	3
E	1	1	1	1	1	1	2	2	3
F	1	1	1	1	1	1	2	2	3
G	1	1	1	1	1	1	2	2	3
H	1	1	1	1	1	1	2	2	3
C	2	2	2	2	2	2	1	1	3
D	2	2	2	2	2	2	1	1	3
I	3	3	3	3	3	3	3	3	1

Figure 7.1 The Matrix consist of final modules for material retrieval objective

Above is the final matrix obtained for the material retrieval objective for redesigned Endopath Xcel Trocar device. Now that the modules are obtained, some of the parts will be renamed for convenience purposes.

A' in this case will be a module consisting of parts A, B and E' is a module consisting of parts E, F, G and below is the new connection diagram for the device

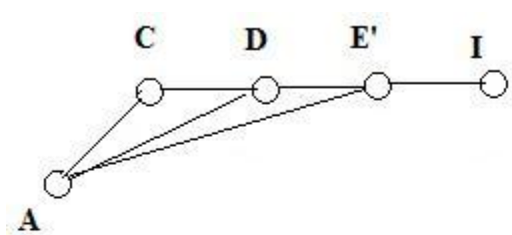

Figure 7.2 The connection Diagram for Material Retrieval objective

Once the connection diagram is obtained, using reverse methodology, we try to obtain all the feasible subassemblies. The feasible subassemblies along with the precedence constraints are given below in table 6.1

Table 6.1 List of subassemblies for Material Retrieval objective for the redesigned device

n=2	n=3	n=4
A'C+	A'CD	A'CDE'
A'D A'D not C	A'DE'	CDE'I
A'E' A'D not E'	CDE'	
CD+	DE'I	
DE'+		
E'I		

Once all the possible subassemblies are obtained, we try to figure out all the possible sequences in order to recover A' and E'. It is a good bet to see if the parts exist as a subassembly or not. In table 6.1, starting from n=4, we obtain the sequence as given in figure 7.3. The AND/OR representation of the disassembly sequence is as given below

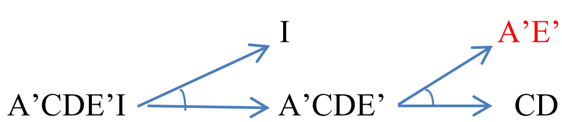

Figure 7.3 AND/OR representation of the disassembly process for material retrieval objective

Below is the transition matrix for the disassembly sequence derived from the AND/OR diagram given in figure 6.3

Table 6.2 The transition Matrix for the disassembly process to recover ABS material

	0	1	2
A'CDE'I	+1	-1	
A'CDE'		+1	-1
CD			+1
A'E'			+1
I		+1	

Once the transition matrix is calculated, we obtain the final Profit of the product

Possible Profit = Possible Revenue from the desired Module $-\sum C_jX_j$ = 100 – (9.4+ 9.8) = 80.8

Appendix II – Profit calculations for Post Life objective

	A	B	C	D	E	F	G	H	I
A	*	*							
B	*	*	*	*	*				*
C		*	*	*					
D		*	*	*	*				
E		*		*	*	*	*	*	*
F					*	*			
G					*		*		
H					*			*	
I		*			*				*

Figure 7.4 The Matrix consist of final modules for Post Life objective

Above is the final matrix obtained for the Post life objective for redesigned Endopath Xcel Trocar device. Now that the modules are obtained, some of the parts will be renamed for convenience purposes.

Module consisting of A and B will be renamed to A’ and D, E, F, G, H and I will be renamed to D’.

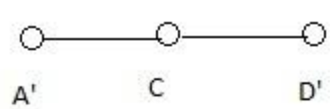

Figure 7.5 The connection Diagram for Post Life objective

Once the connection diagram is obtained, using reverse methodology, we try to obtain all the feasible subassemblies. In this case it is apparent that there are only 2 possible subassemblies, which are, A’C and CD’

Once all the possible subassemblies are obtained, we try to figure out all the possible sequences in order to recover D’. In this case there is only possible sequence. The AND/OR representation of the disassembly sequence is as given below

Table 6.3 The transition Matrix for the disassembly process to recover reprocessable material

	0	1
A’CD’	+1	-1
A’C		+1
D’		+1

Once the transition matrix is calculated, we obtain the final profit of the product

Possible Profit = Possible Revenue from the desired Module $-\sum C_jX_j = 100 - (9.8) = 90.2$

Curriculum Vita

Karthik Varma M Koppella was born on December 15, 1985 in Visakhapatnam, India. The only son of Dr. Lakshmipathi Raju and Dr. Lalitha Kumari, he graduated from Jawaharlal Technological University, India with a Bachelor of Technology degree in Electronics and Communications Engineering in fall of 2009. He enrolled in University of Texas at El Paso in spring 2011 to continue his study with Master of Science in Industrial Engineering. While at the university, he worked as a research assistant at Intelligent Systems Engineering Laboratory and as a teaching assistant for Strategic Design for Manufacturing Processes in Industrial Engineering Department. He worked as an Intern as a Lean Engineer in AsteelFlash in California for a period of 5 months. He has technical certifications in Six Sigma from Institute of Industrial Engineers, Lean Manufacturing Certificate from Texas Manufacturing Assistance Center

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